Potential for Volumetric Bit-Wise Optical Data Storage in Space Applications

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Development of Volumetric Bit-Wise Optical Data Storage for Space and Ground Applications

Tom Milster, University of Arizona

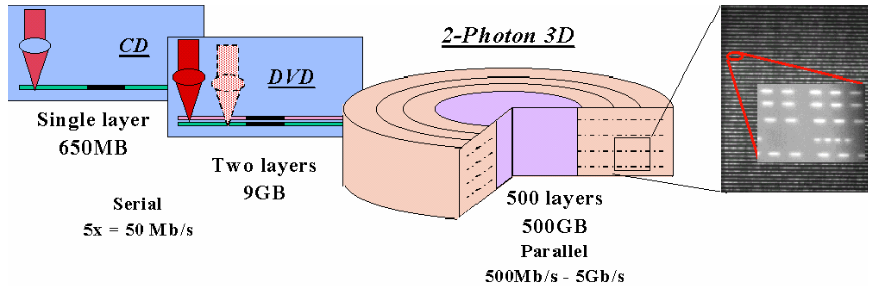
Description and Objectives

Description:

Investigate three-dimensional optical memory for space and ground-based applications. The 2-photon effect is used to produce multiple-layered media that have extremely high capacity and high performance.

Objective:

Evaluation and development of large capacity, high performance, low cost, rugged, reliable secondary memory. Achieve 1Tb/in^2.



2-Photon storage 1" diameter disk holds 500 GB with 500 Mbit/sec minimum parallel readout speed.

Accomplishments

Completed media testing for low-earth orbit environment

Developed advanced servo systems for write/read

Developed advanced engineering model (AEM)

Analyzed system performance and projected potential

Suggested new media geometries that maximize potential

Project History

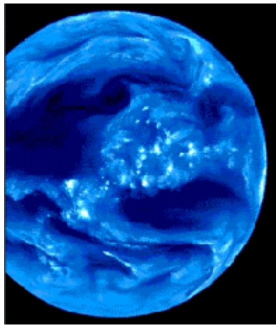
2001 – Research contract established between NASA ESTO and University of Arizona (Initial TRL3)

2003 – Completed three-year NASA contract at TRL 4

2004 – Publication of results and soliciting new funding

Outline

- Introduction
- Technology Review
- Media Physics
- Advanced Engineering Model (AEM)
- Technology Potentials
- Conclusions

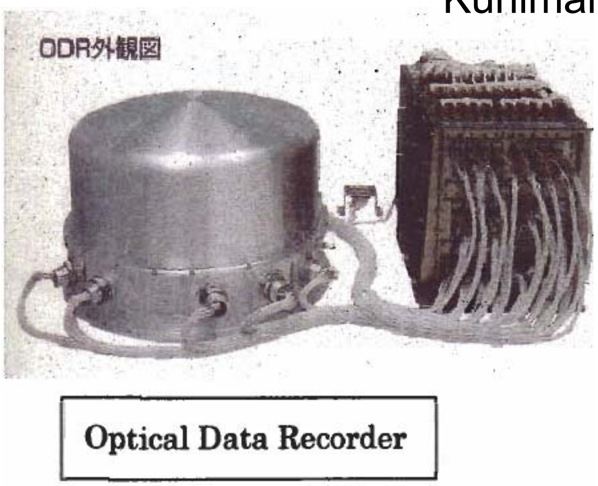


Motivation

- On-board processing systems for Earth Science Enterprise demand ever-increasing data rate and storage capability.
- Semiconductor memory for secondary storage is large, consumes power and is expensive.
- Volumetric storage offers lower cost, an order of magnitude smaller size and mass, and lower power requirements.
- Example: cubic bit having dimension L = 650 nm yields 1 tera-bit per cubic centimeter.
- Our work is highly leveraged from efforts at University of Arizona and Call-Recall, Inc., with 2-photon volumetric media.

Precedent: Japanese Optical Disk Drive for Space Use

(World's first optical drive in space)
Kunimaro Tanaka, Teikyo Heisei University



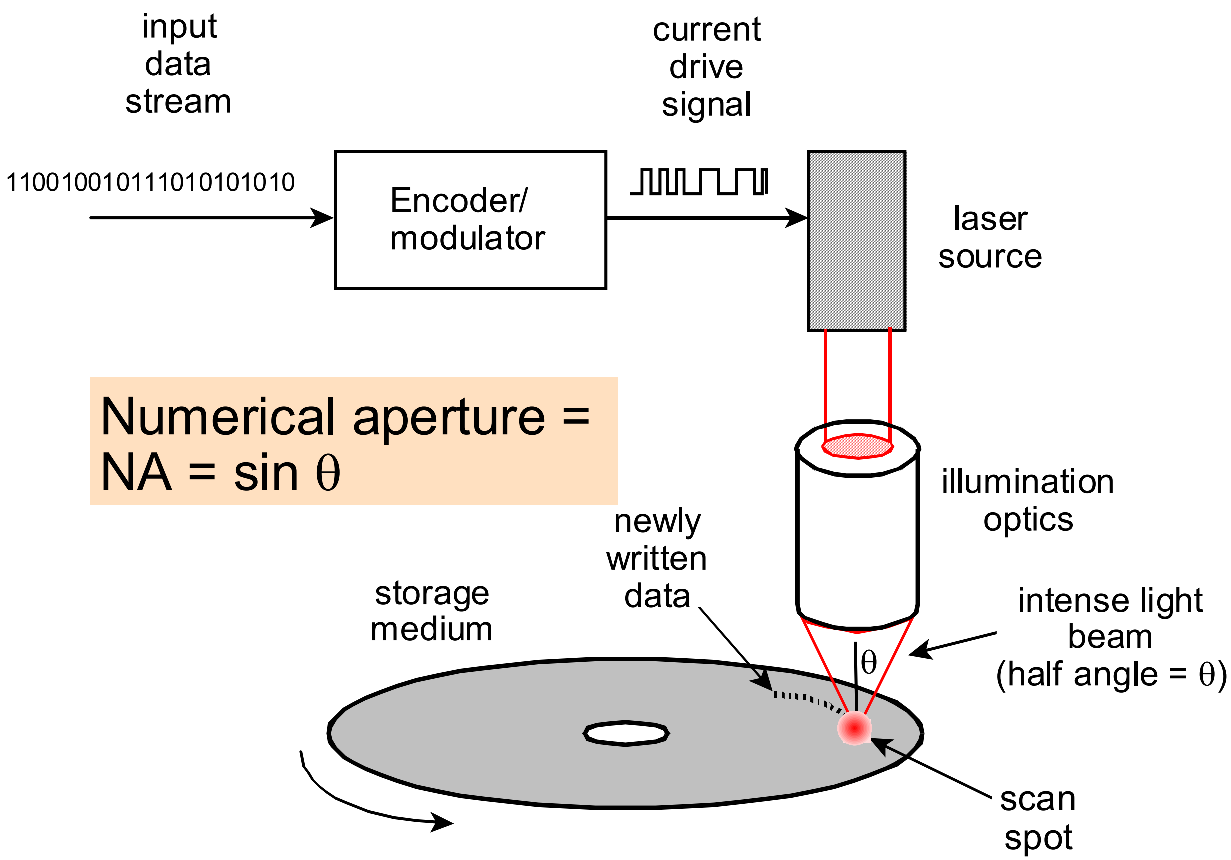
Launch

Dec 14, 2002

Earth observation data stored when out of range of telemetry station in Australia, then downloaded when in range.

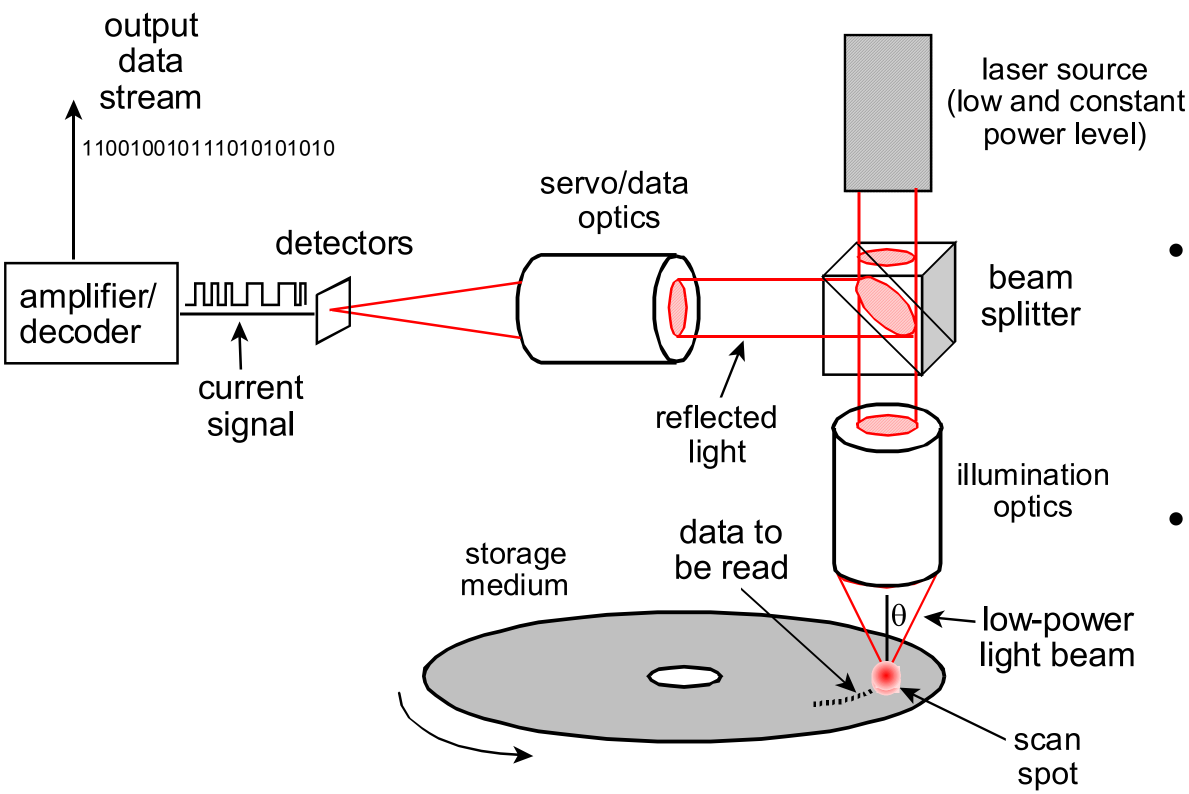
Technology Review

Writing On a Spinning Disk
(Single Layer)



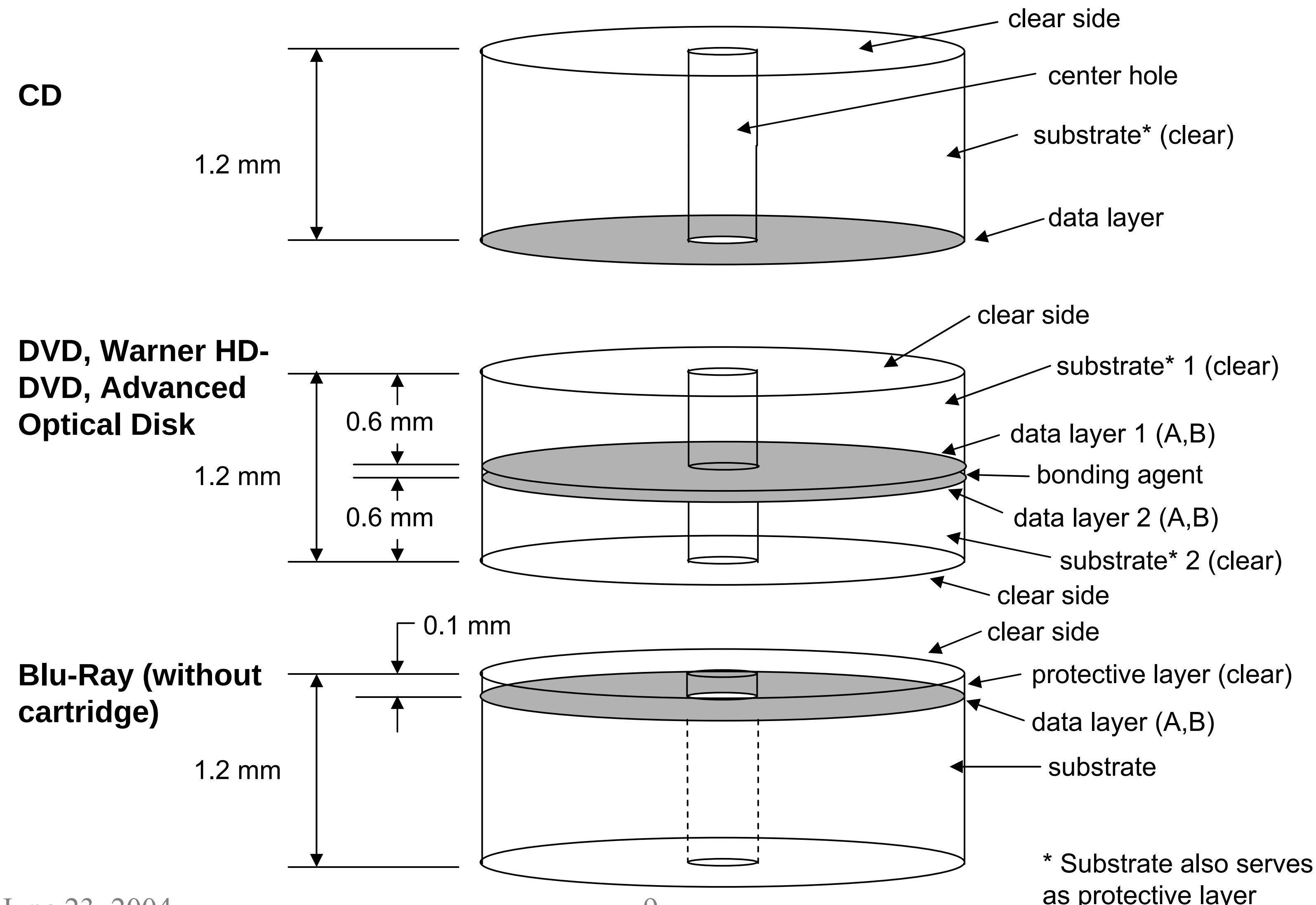
- Input data stream is encoded into a drive signal for the laser
- Laser pulses energy through the illumination optics
- Light beam is focused to an intense laser spot
- Spot alters media as disk rotates

Reading Data From a Spinning Disk
(Single Layer)



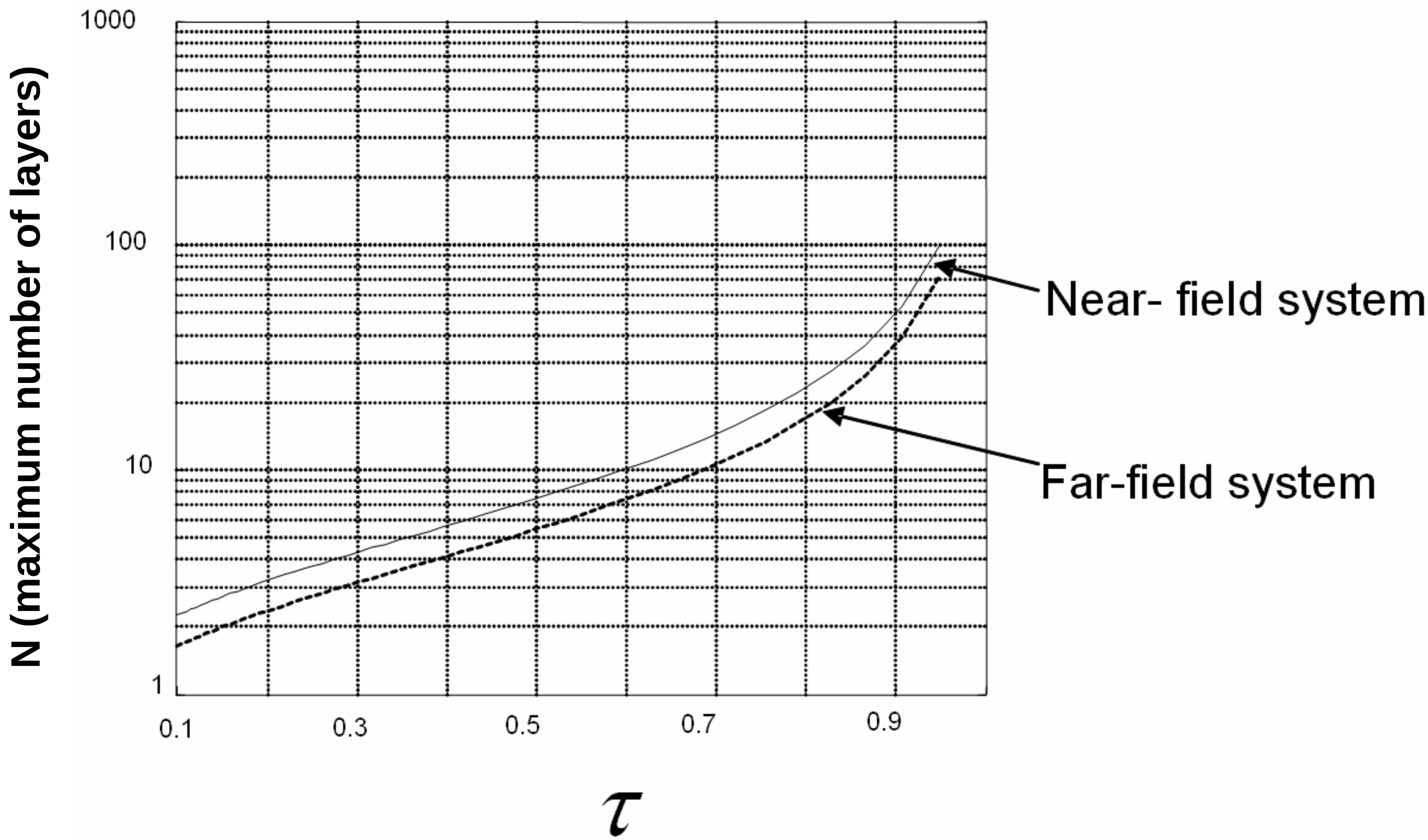
- Low-power laser beam scans data pattern on spinning disk.
- Fluorescence is directed with a beam splitter to detectors.
- Detectors produce a current signal, which is then decoded into user data.

Commercial Sector Technology Trends



OPTICAL DATA STORAGE CENTER

Increase Capacity by Increasing Number of Layers



Maximum number of layers limited by transmission τ of each layer.

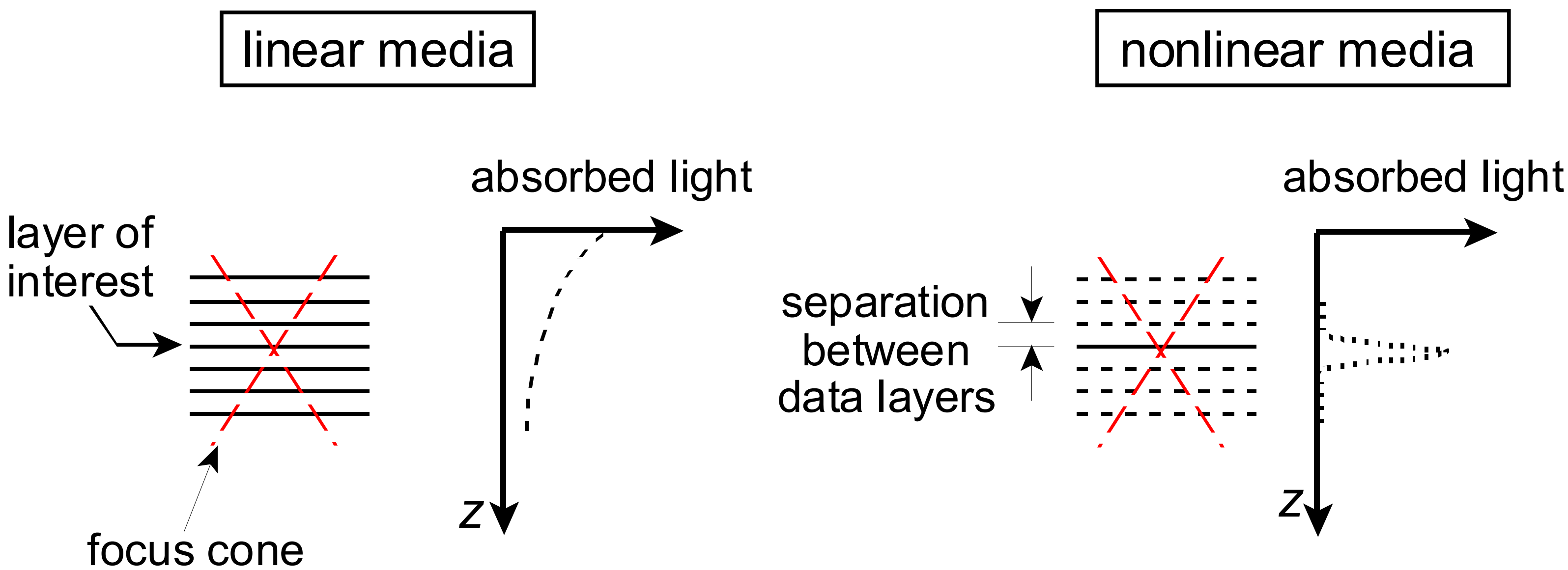
Conclusion

- Capacity/layer can be increased up to 35 GB by reducing bit length using advanced PRML.
- Multi-layer can be extended up to 8-layer by decreasing thickness of spacer layers.
- Transfer-rate can be increased up to 250 Mbps even at 10,000 rpm.
- Total capacity of Blu-ray disc can be extended up to 280 GB (35 GB x 8).

Primary Limitation to Capacity is the Small Number of Layers

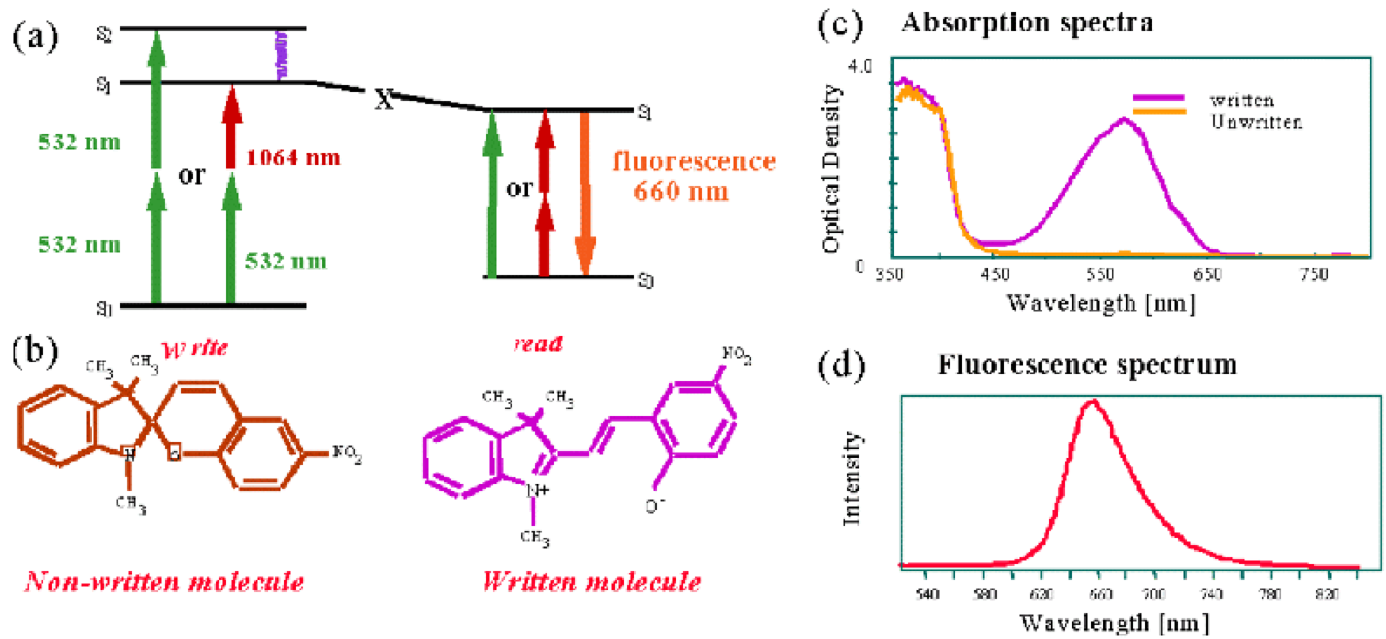
2-Photon Media Physics

Two-Photon Nonlinear Media Absorption
(Many Layers)



- Nonlinear absorption characteristics can be used effectively with volumetric memories to isolate a layer of interest.

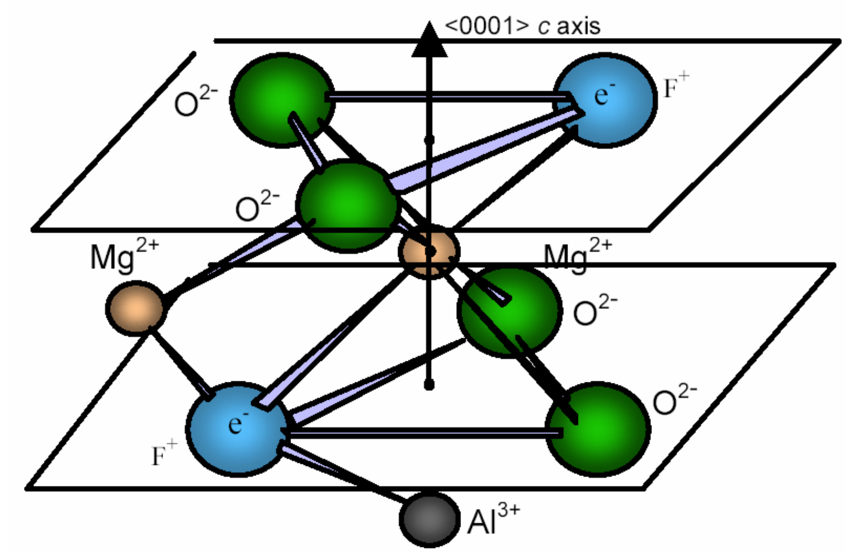
C/R Two-Photon Media Characteristics



- Energy bands of the written and unwritten molecule result in different absorption and emission characteristics.
- A two-photon process is used for writing.

Improved Media

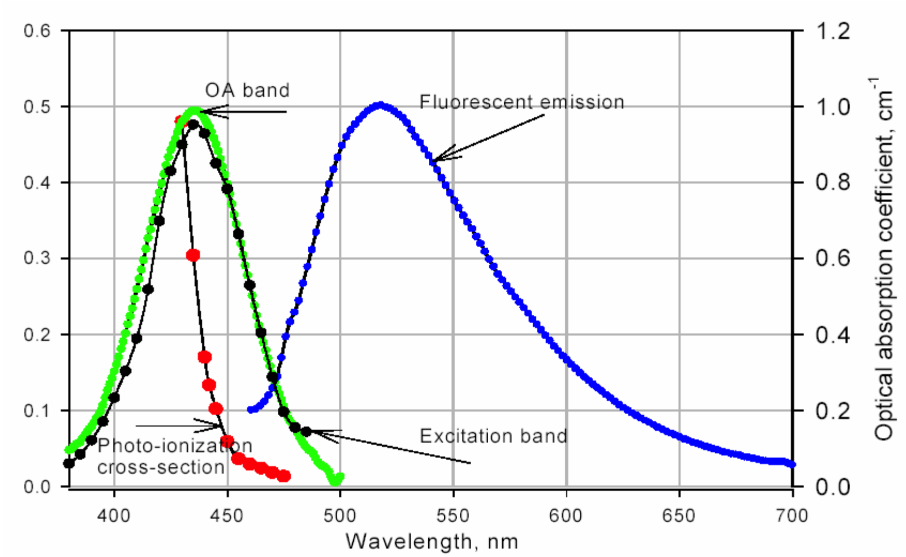
(Possible 2-Photon Media from Landauer*)

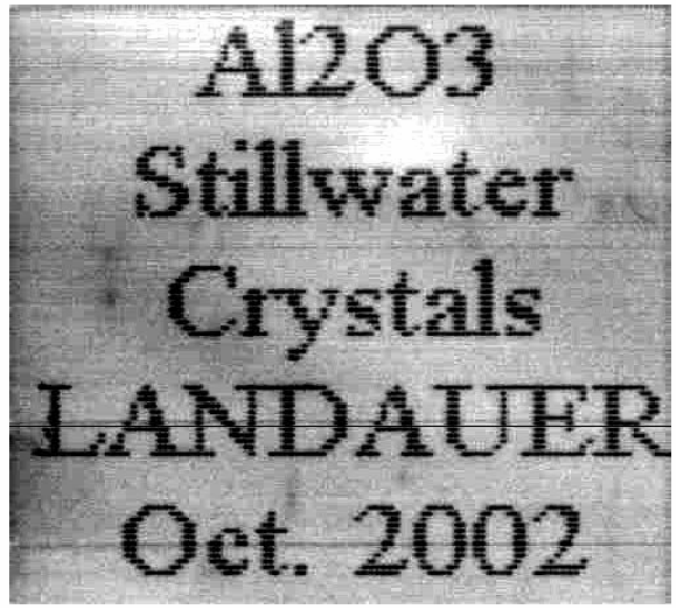


- Sapphire-base crystal with impurities to create trapping centers for absorption and subsequent fluorescence.
- Sapphire crystalline structure exhibits many positive mechanical characteristics

*Presented at ODS '03 in Vancouver

Improved Media
(Landauer 2-Photon Media)





- Energy-band structure contains an intermediate level in the absorption band that reduces power requirement on writing.
- Media can be written and read out with commercially-available diodes.
- The media are erasable.
- Disk surface should not be sensitive to temperature effects.

Two-Photon Media Physics Summary

- Homogeneous, transparent ($\tau \sim 1$) substrate allows a large number of layers.
- Two-photon absorption for writing requires high laser power at λ_1.
- Readout uses low-power laser at λ_2 for illumination.
- Data light is from fluorescent marks at λ_3 with limited data rate per beam.
- Plastic media surface sensitive to temperature.
- Media insensitive to high-energy ions.
- Media sensitive to high-energy protons with exposure greater than 20,000 krad.
- Improved media possible with robust sapphire substrate.

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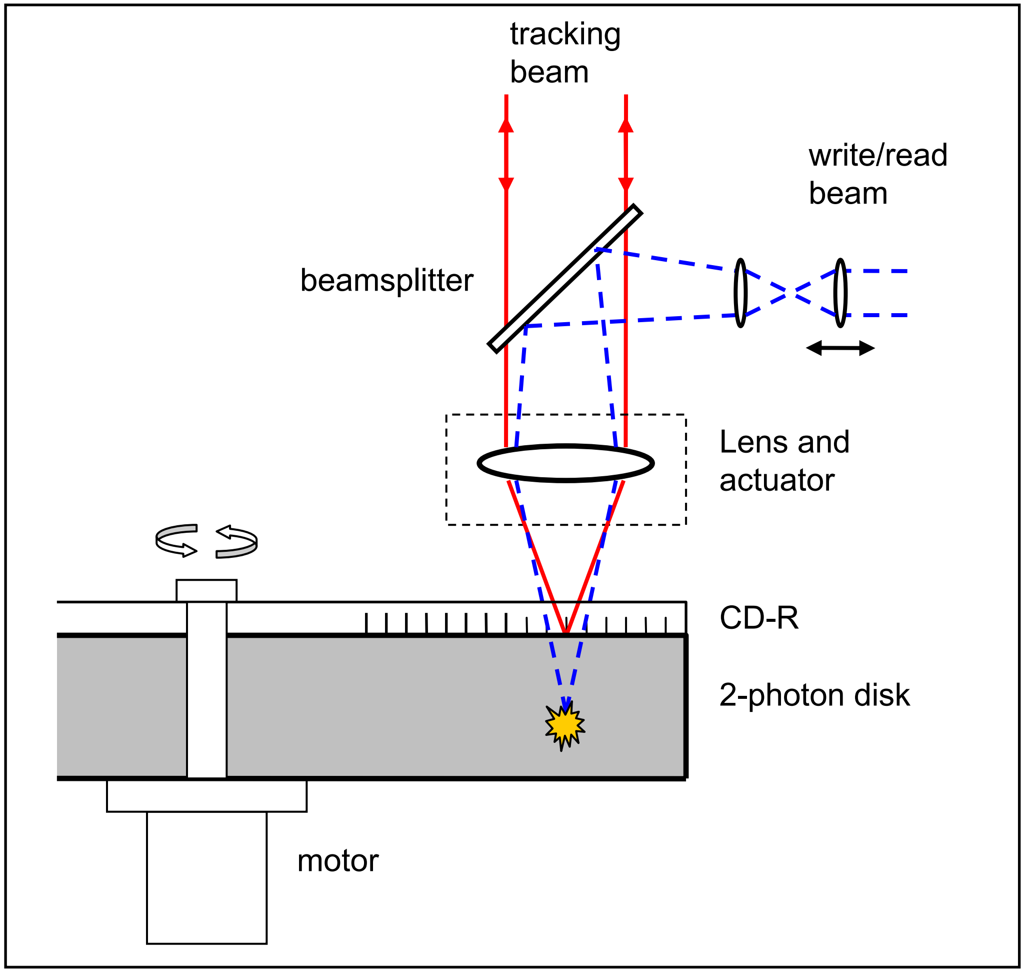
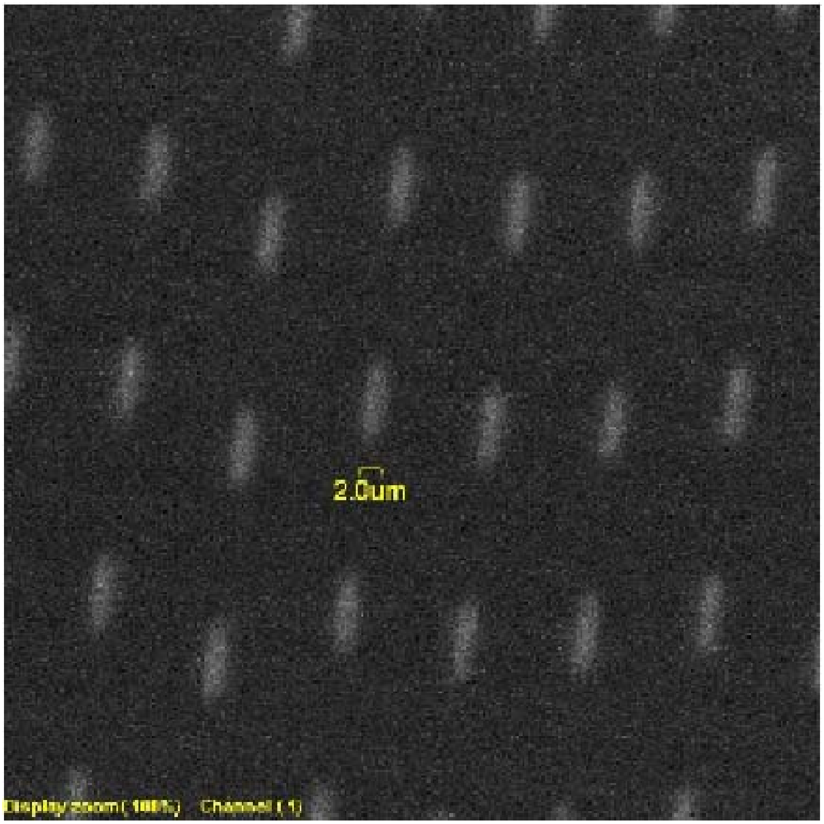
The Advanced Engineering Model (AEM)

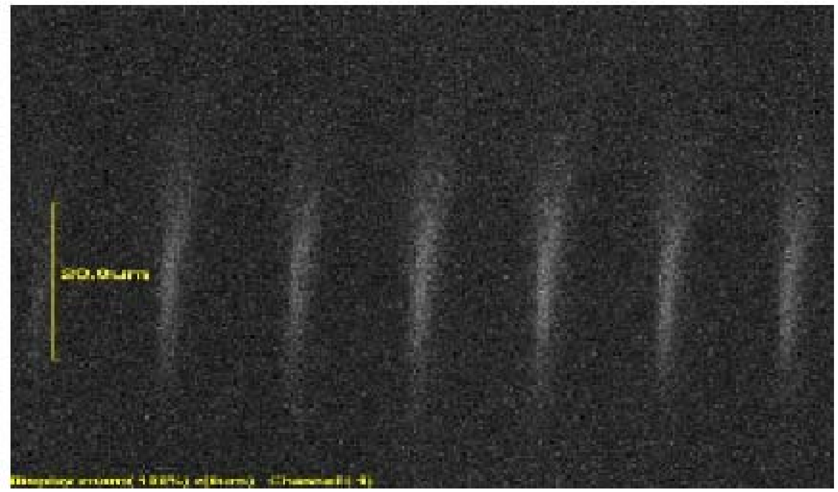
AEM Servo Design



- The tracking beam and the write/read beams are combined through a single actuator.
- The two beams are focused through the same lens to different layers in the disk pair, utilizing adjustable compensation optics.

AEM Data Marks

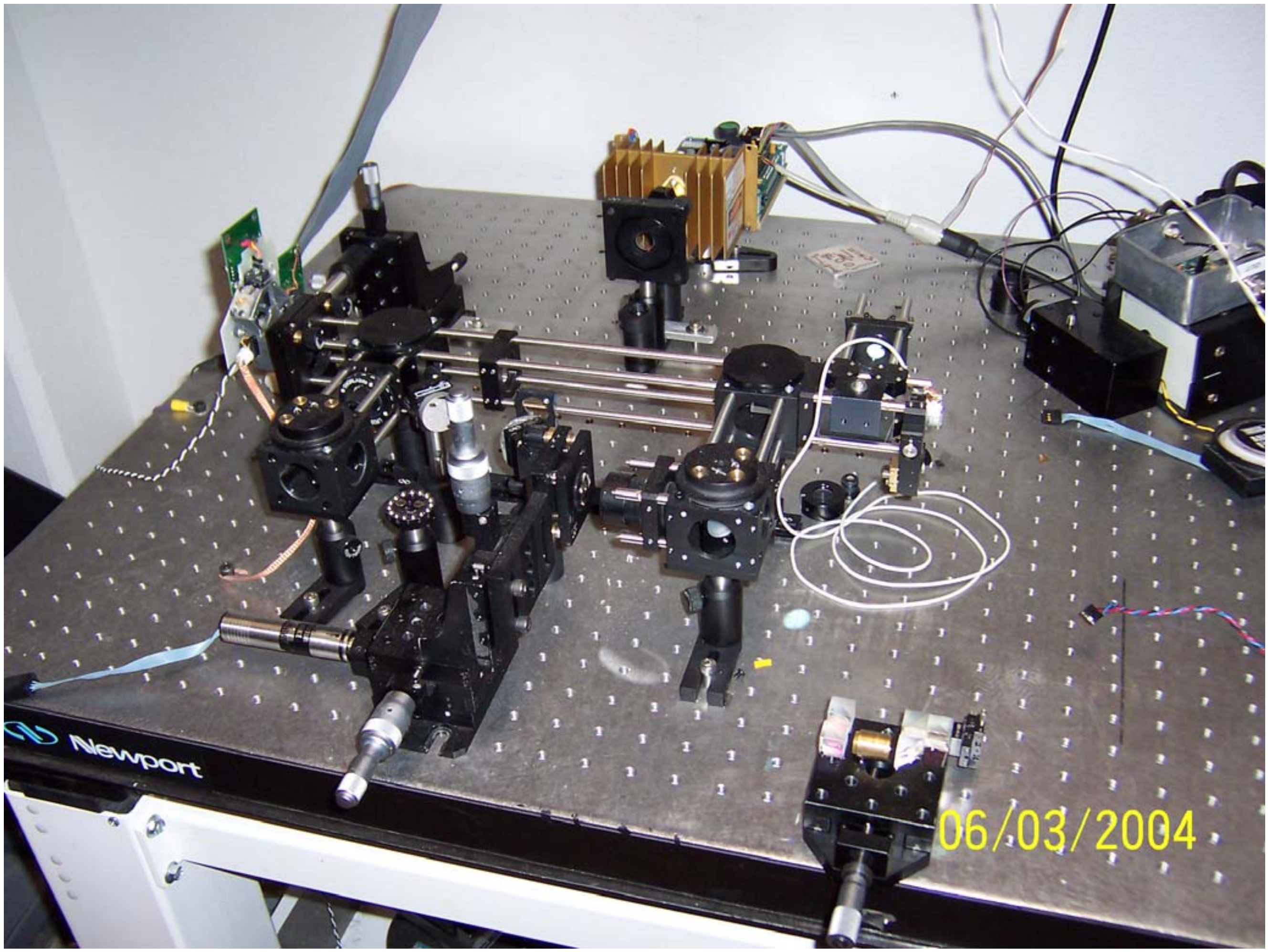


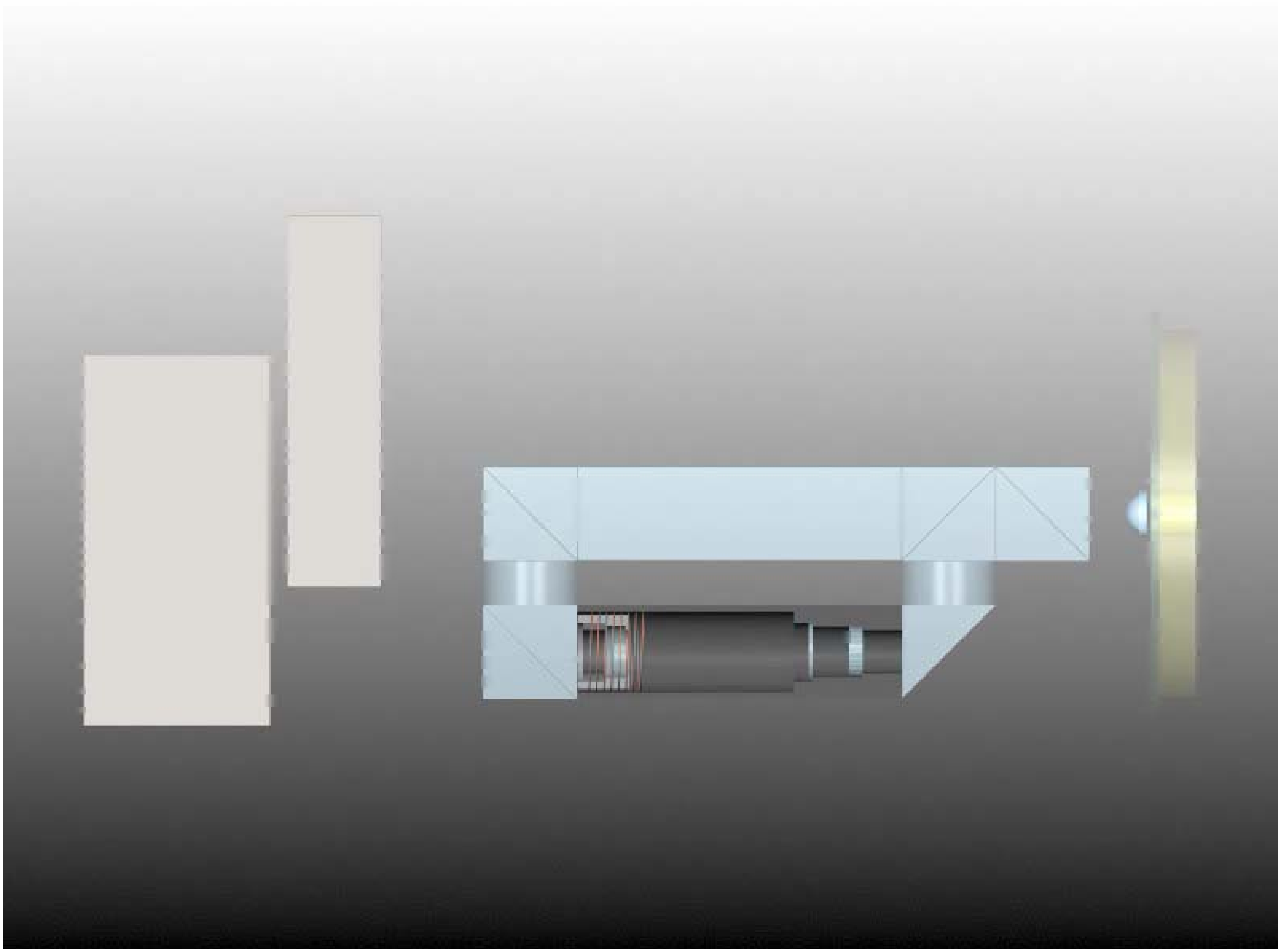


Depth dimension

Transverse plane (Top view)

AEM Experimental Layout





AEM

Technology Potential

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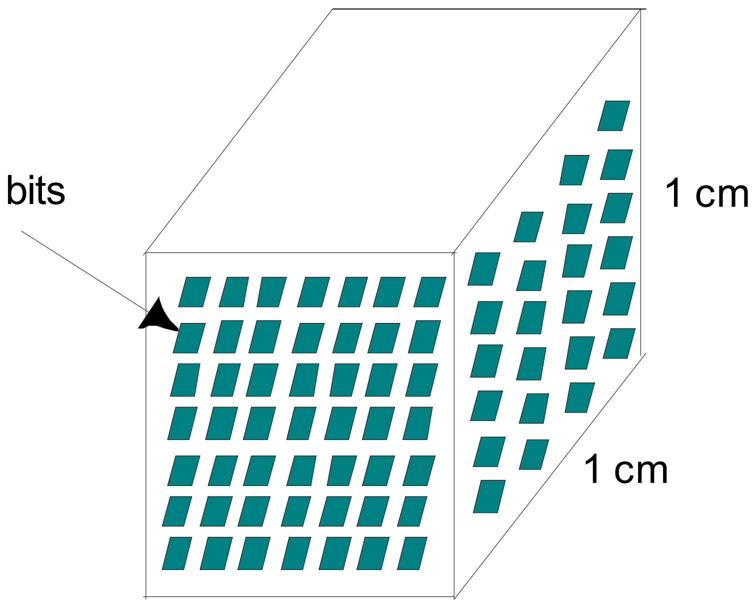
What Limits Storage Capacity?

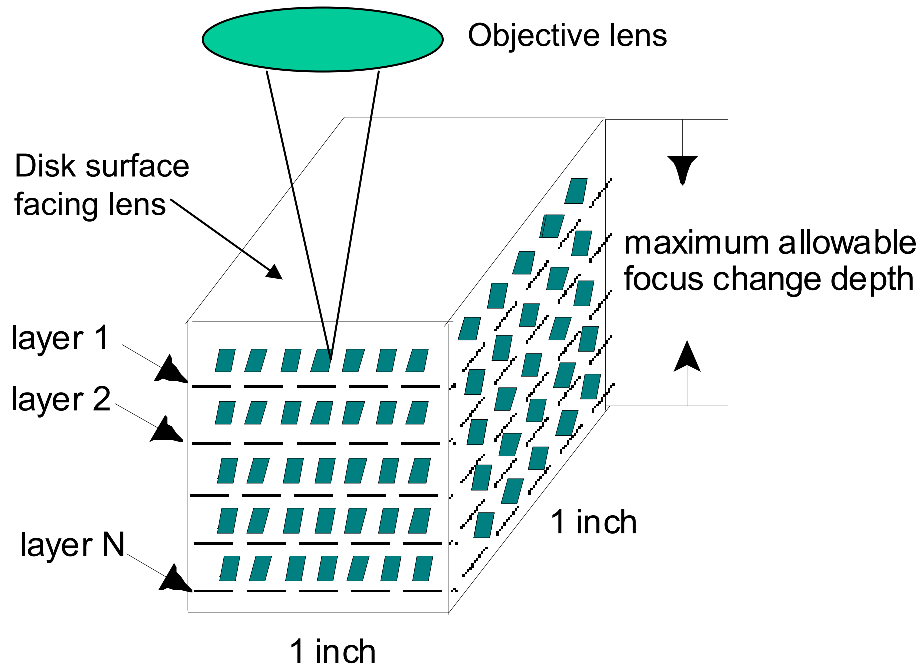
Storage capacity in a 3-D disk is limited by the amount of aberration that can be corrected as the optical system focuses through layers.

Volumetric Density



Volumetric density = 1 / bit volume

Effective Surface Density



Effective surface density= N * (1 / bit surface area)

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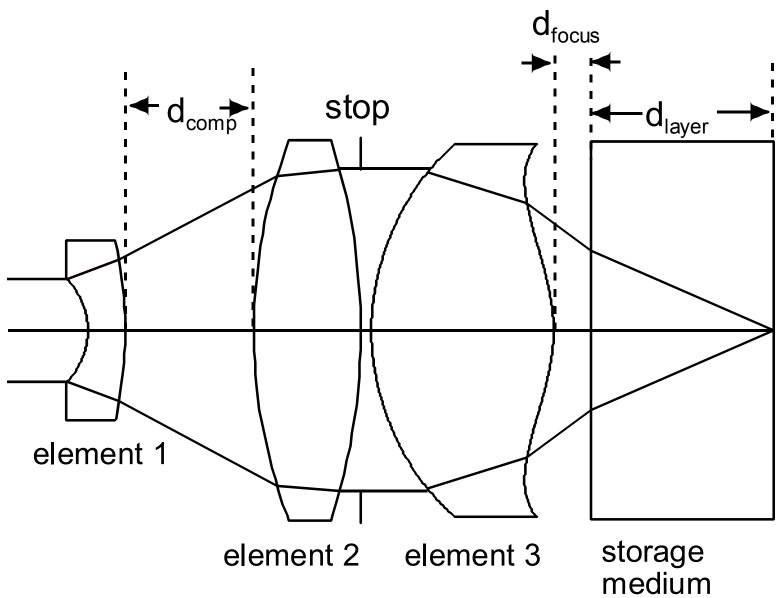
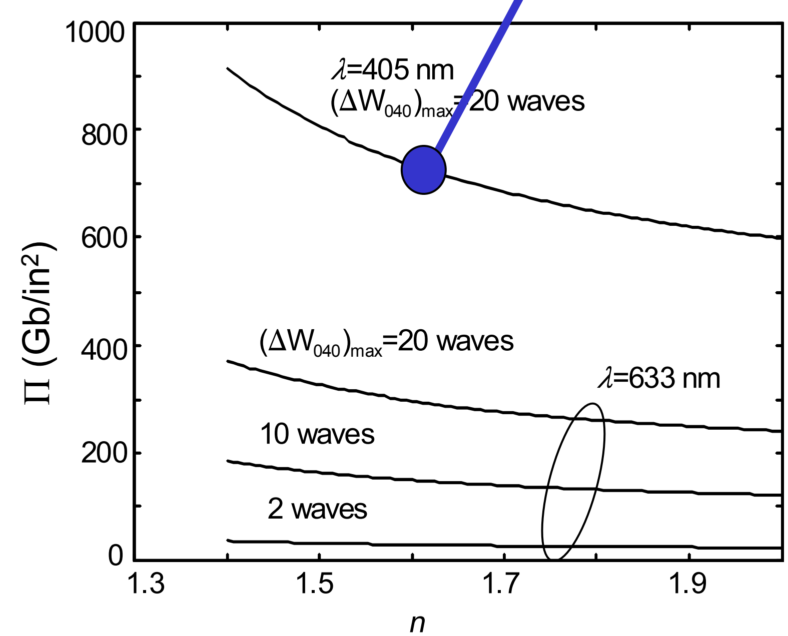
What is the *Practical* Expectation for Storage Density?

Far-Field System



1 LOC* = 16 disks



- Far-field optics

* 1 Library of Congress (LOC) = 20 TB

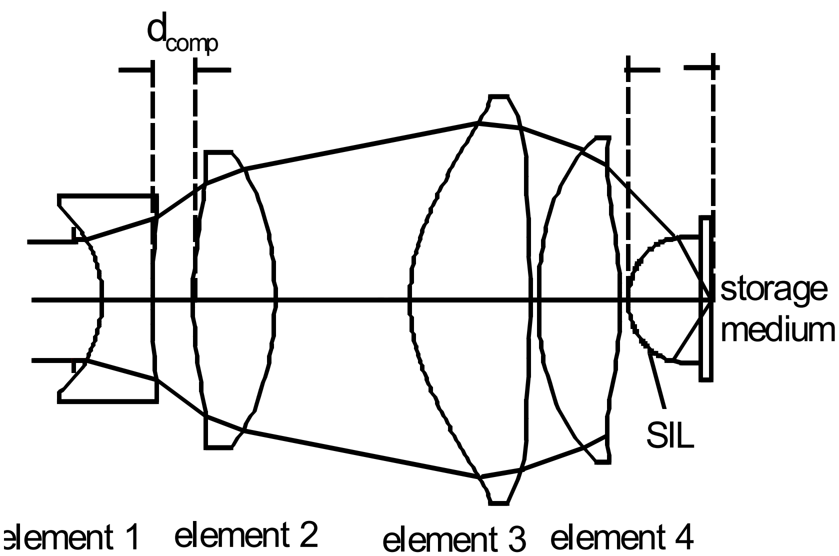
(Text data as of Y 2000)

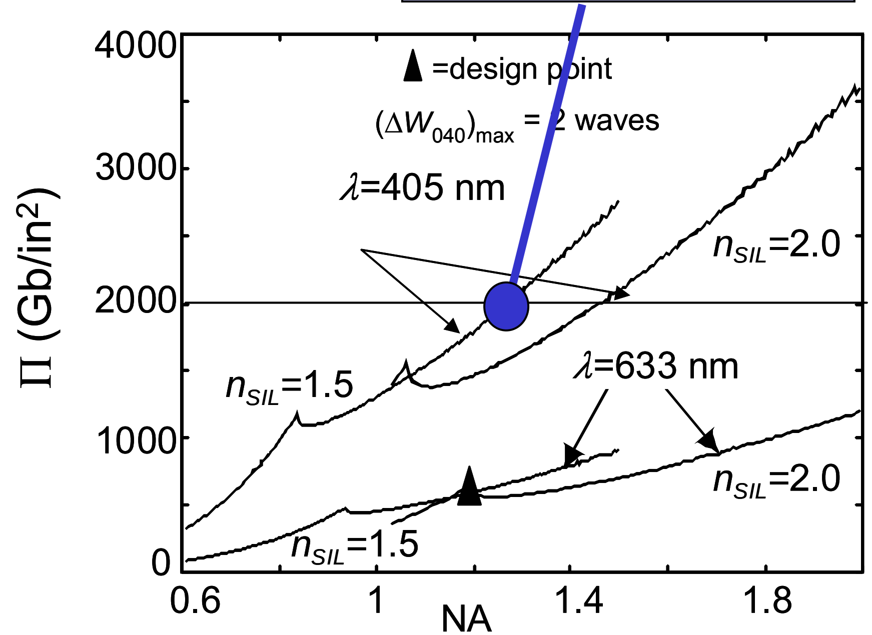
- Π = effective surface density (bits/unit area)
- n = storage refractive index
- ΔW = aberration compensation

What is the *Practical* Expectation for Storage Density?

Near-Field System

1 LOC* = 6 disks





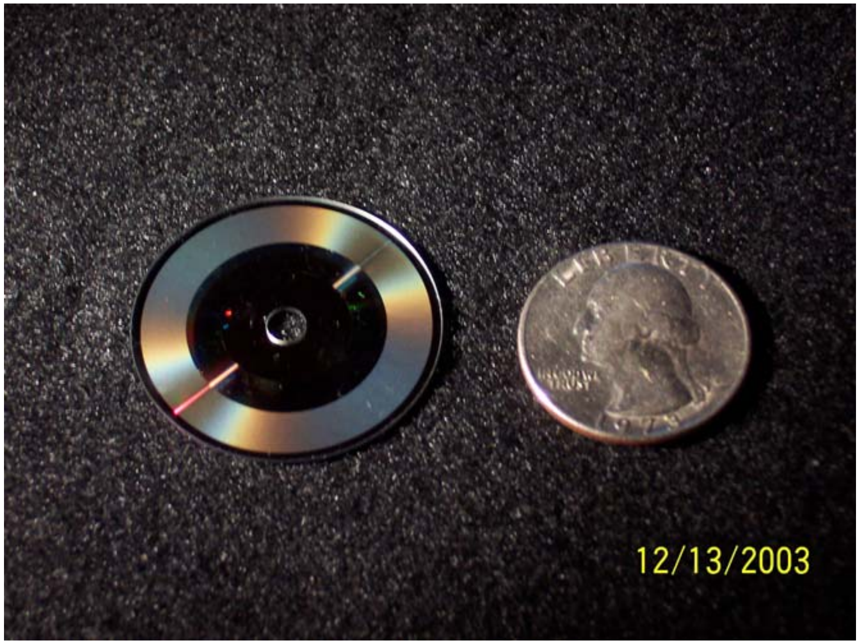
- Near-field optics, NA = 1.2

* 1 Library of Congress (LOC) = 20 TB

(Text data as of Y 2000)

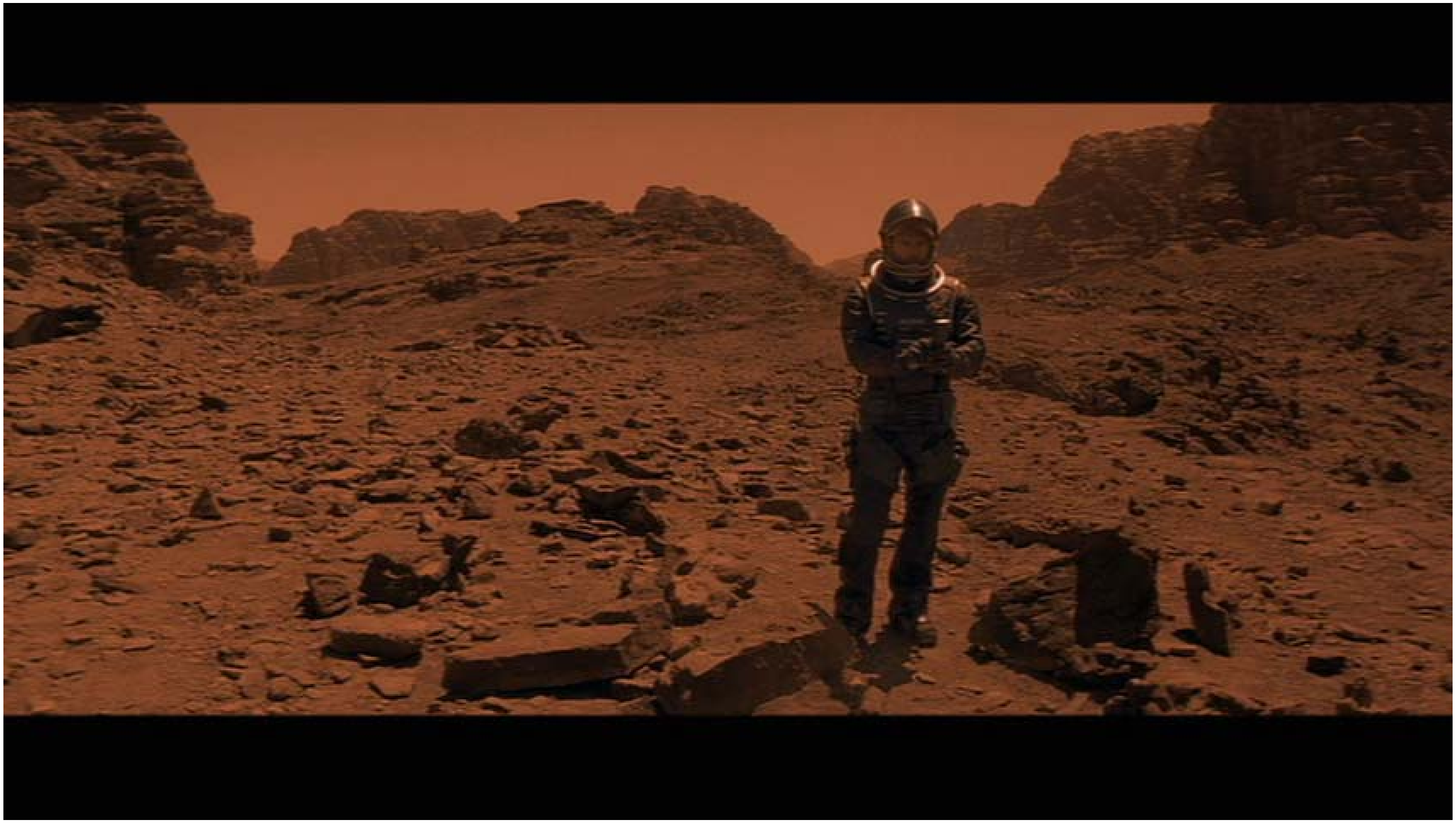
- Π = effective surface density (bits/unit area)
- *n* = storage refractive index
- ΔW = aberration compensation

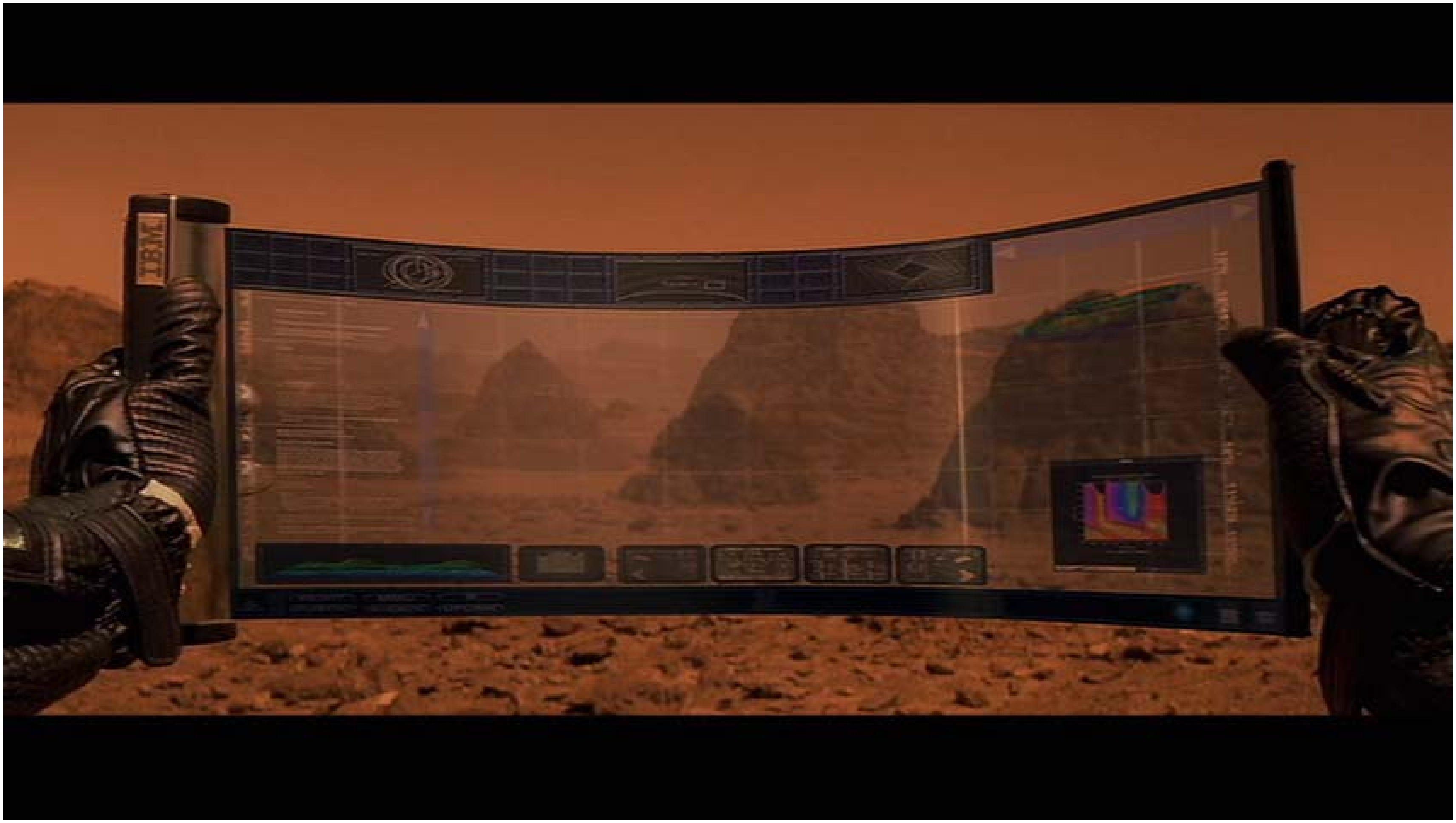
Miniaturized Drives and Media



- 1” diameter media → 590 GBytes
- 2” diameter media → 2.5 TBytes
- 3” diameter media → 5.6 TBytes

Future Work




IBM

Low-Power 1TB Memory Module for Data Scroll

Memory Module

- 30 mm dia
- 20 mm high
- Rugged

Conclusions

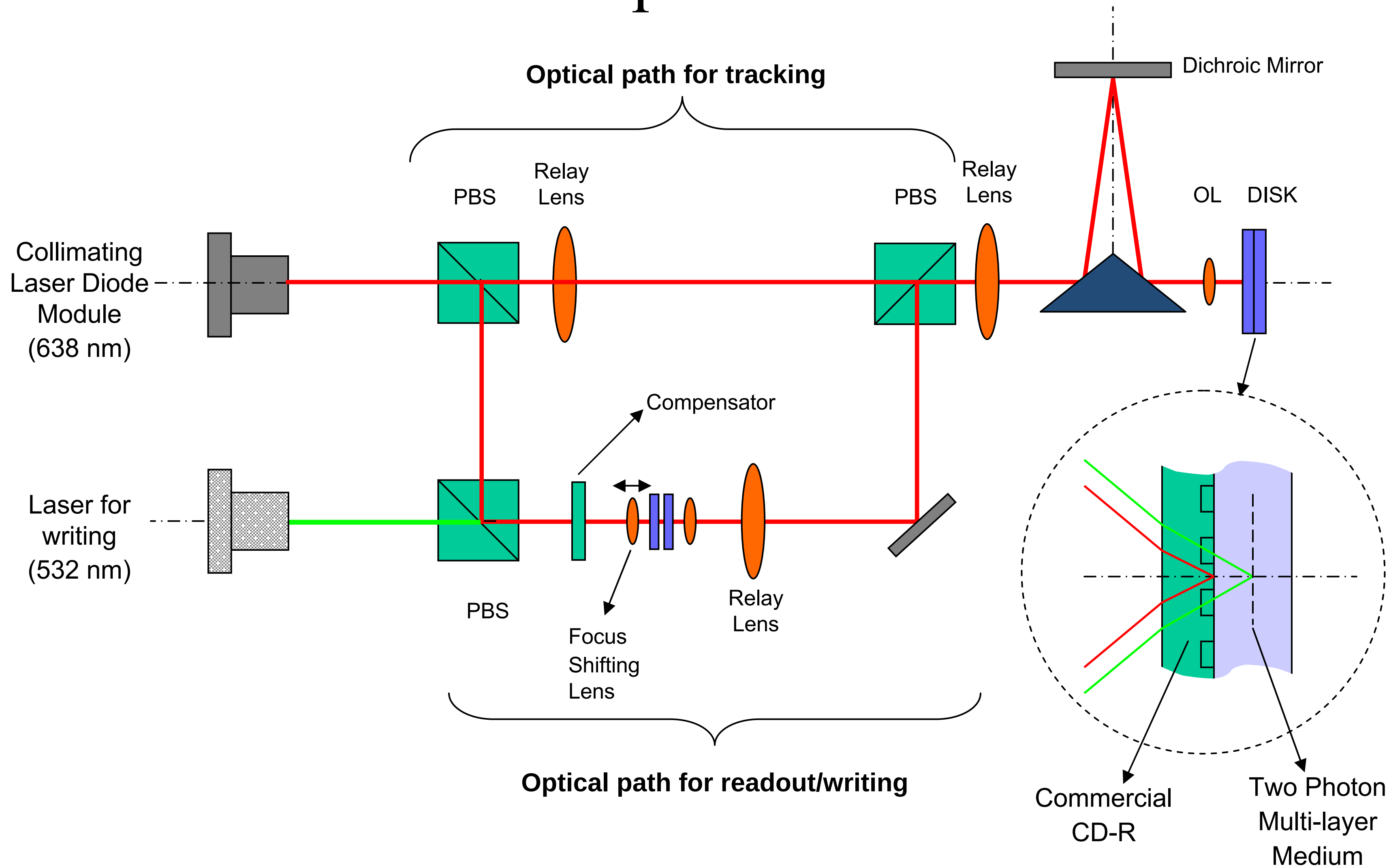
- Bit-wise volumetric optical data storage is shown to hold great promise for spacecraft and ground applications.

- Miniaturization and improvement of the optical system has resulted in a system description of less than 8 in^3 using off-the shelf components, with further miniaturization possible. This format can hold over 2 TB in a low-power configuration.

- The PMMA substrate used in the initial study is too sensitive to temperature, requires too much laser power for writing, and is not erasable. An improved medium (like Landauer's sapphire disks) should be the focus of the next stage in the research, and the application of our systems research should be directed to the new medium.

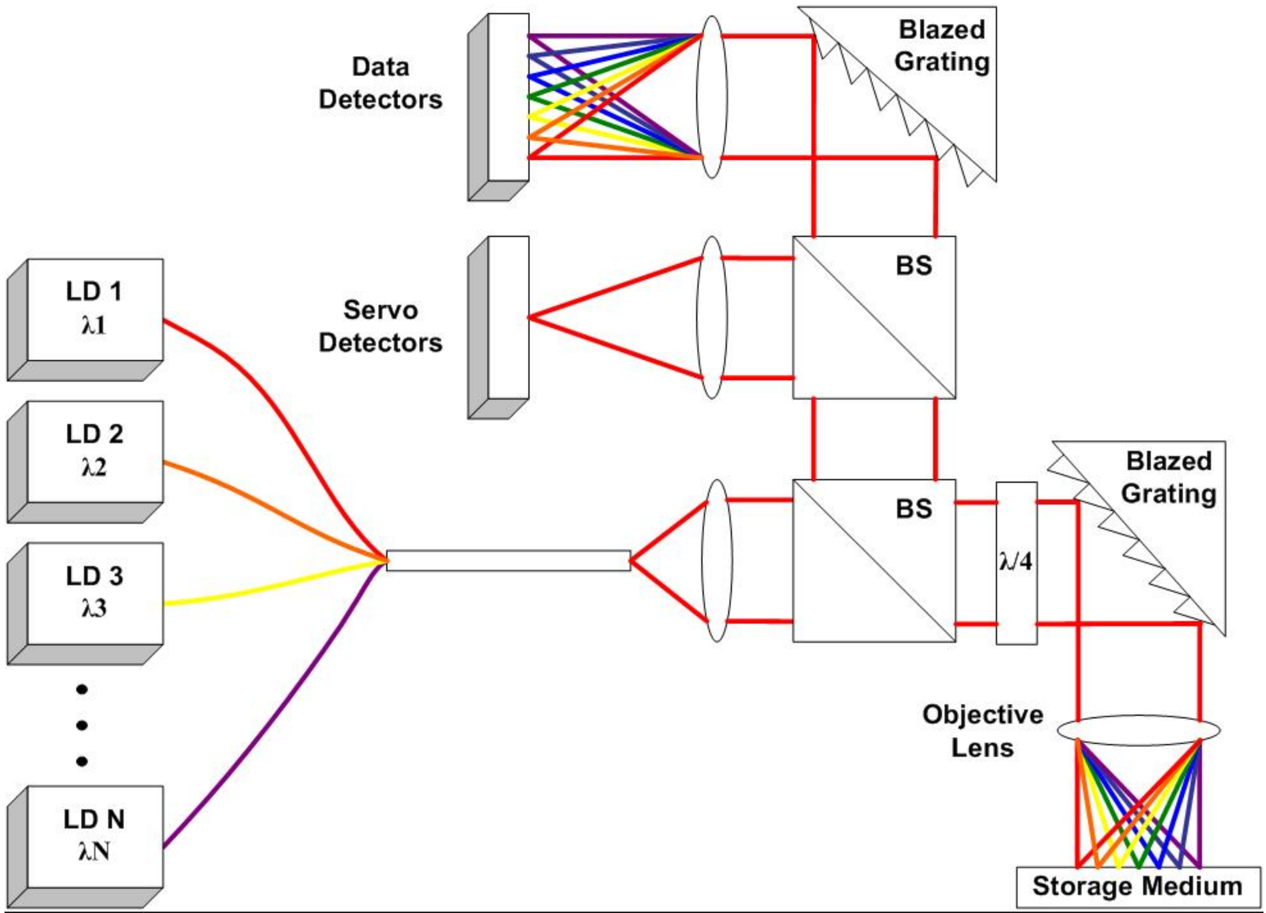
- Several new system configurations are suggested that have obvious applications in future space and ground missions. Cylindrical media are well suited for volumetric systems.

AEM Optical Path

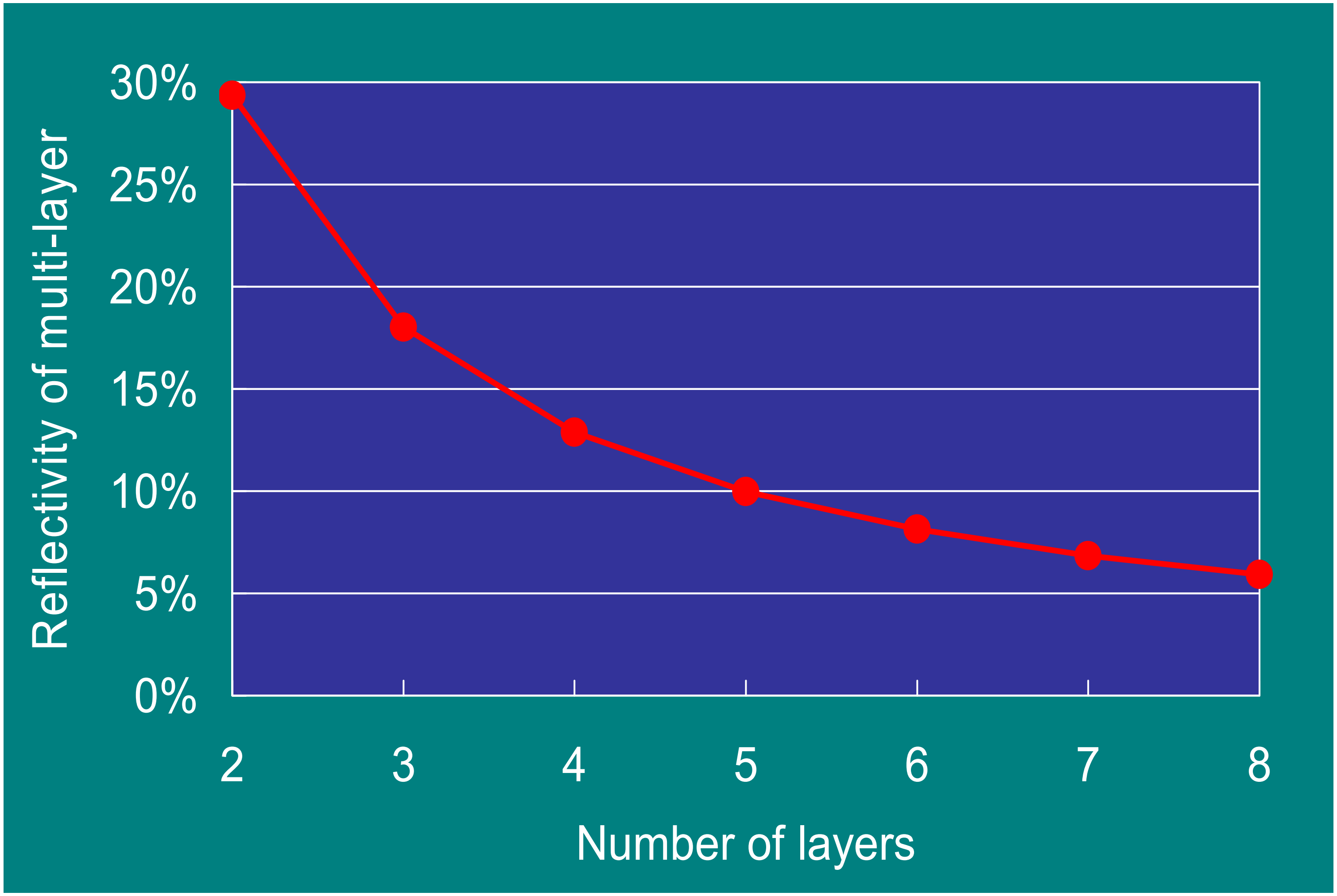


Wavelength-Domain Multiple-Beam System

(Used for readout illumination)

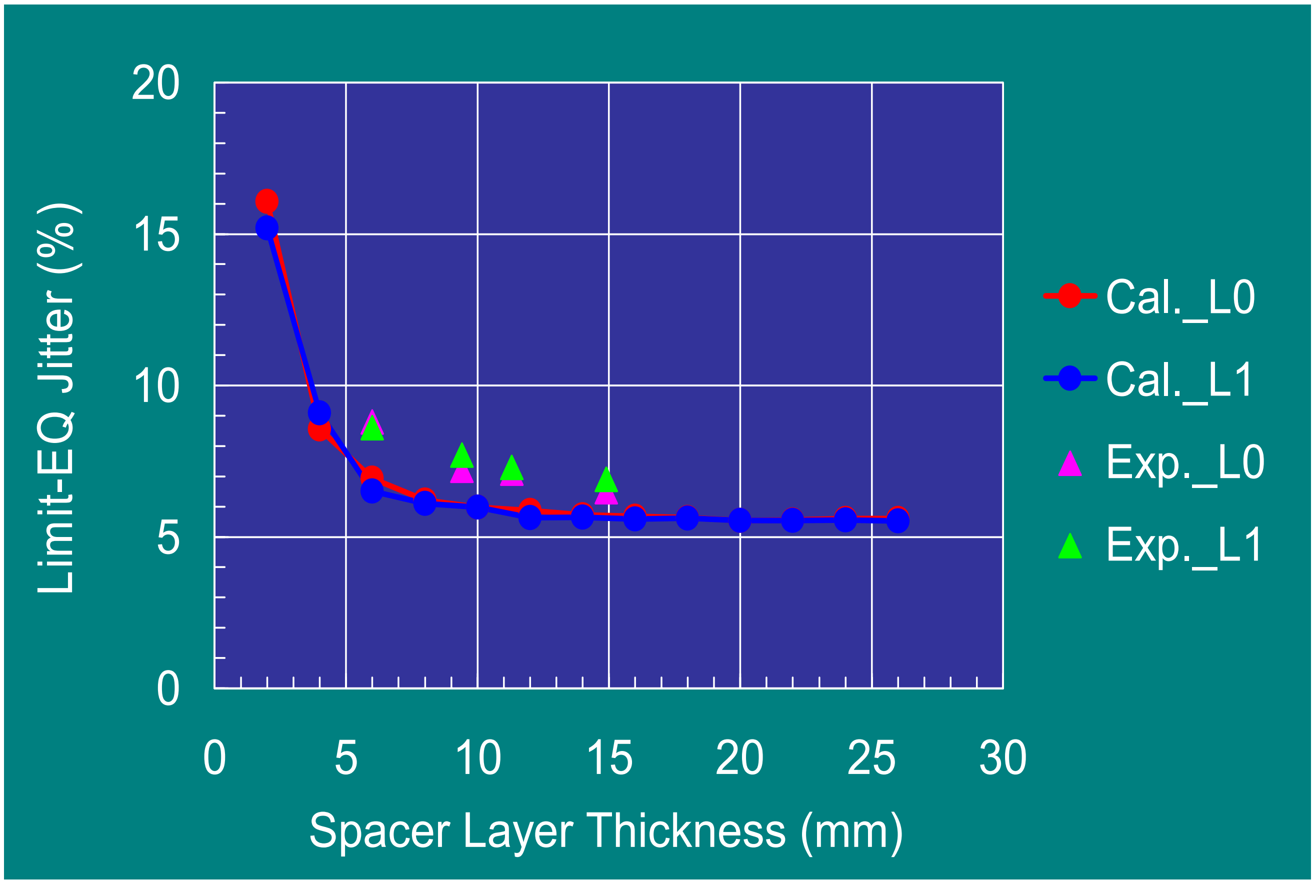


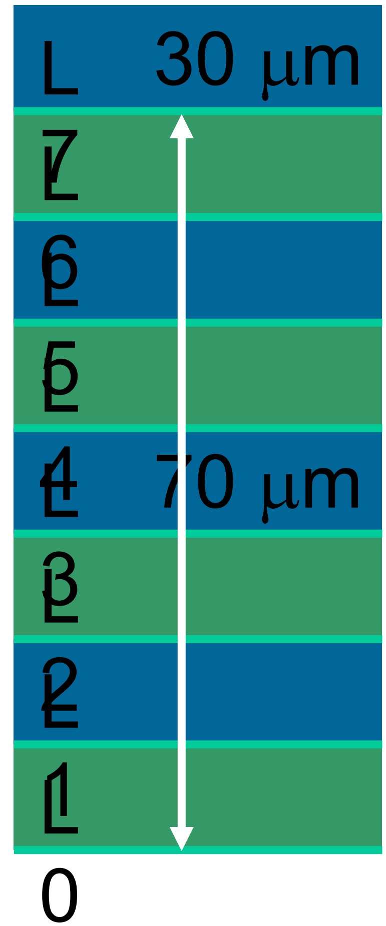
Achievable reflectivity of Multi-layer ROM disc



Minimum spacer layer thickness

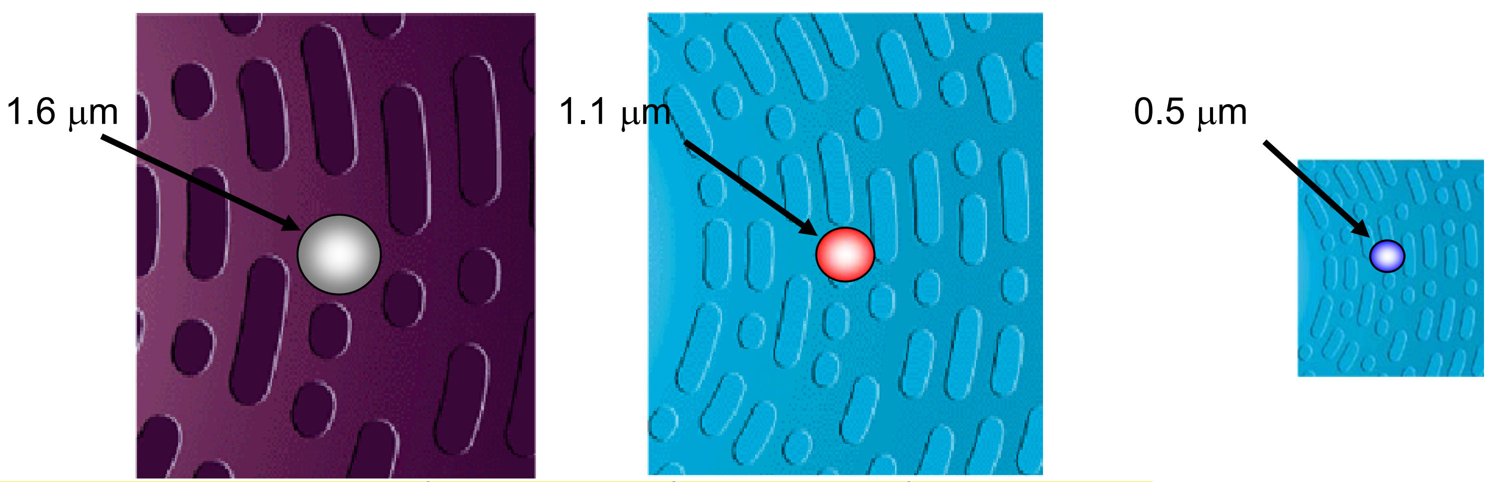
- Using around 10 μm spacer, 8-layer disc can be realized.





Where We Are Today

CD (0.7 GB) DVD (4.7 GB) BD (20 GB)

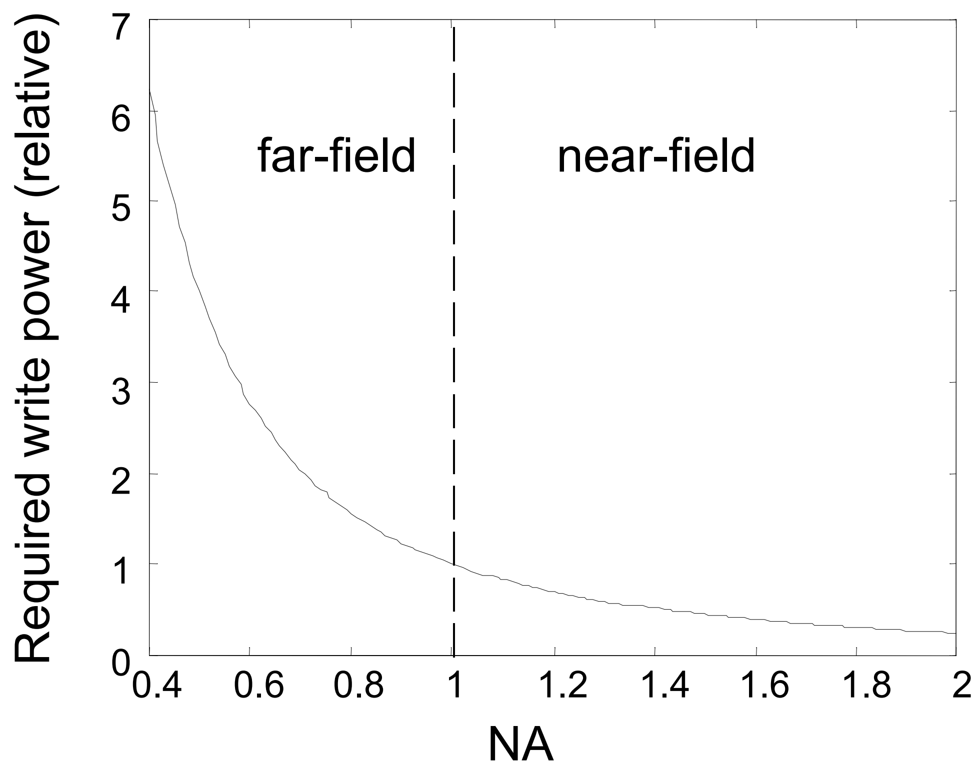


	CD	DVD	BD/Blu-Ray
Wavelength (μm)	0.785	0.650	0.405
Numerical Aperture	0.47	0.60	0.85
FW1/e^2 Spot Size (μm)	1.6	1.1	0.5
Track Pitch (μm)	1.6	0.74	0.32
Min Mark Length (μm)	0.83	0.40	

(Double-layer BD with Super-RENS may reach 120 Gb/in^2 in 5 years)

Smaller Spots and Higher Capacity

Writing Characteristic



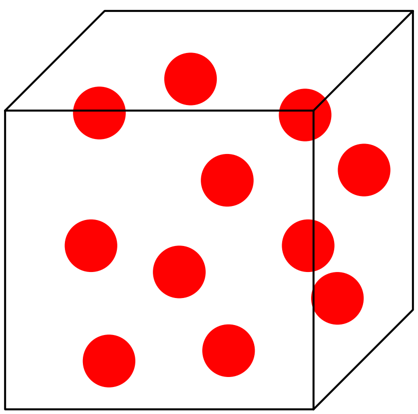
Peak power required in the writing system ~ $1/NA^2$

Near-field system needs much lower peak power to write marks

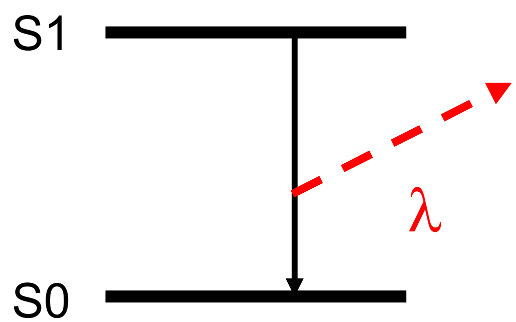
How Many Photons for Readout?

N molecules per unit volume

(~ 10^4 μm^{-3})



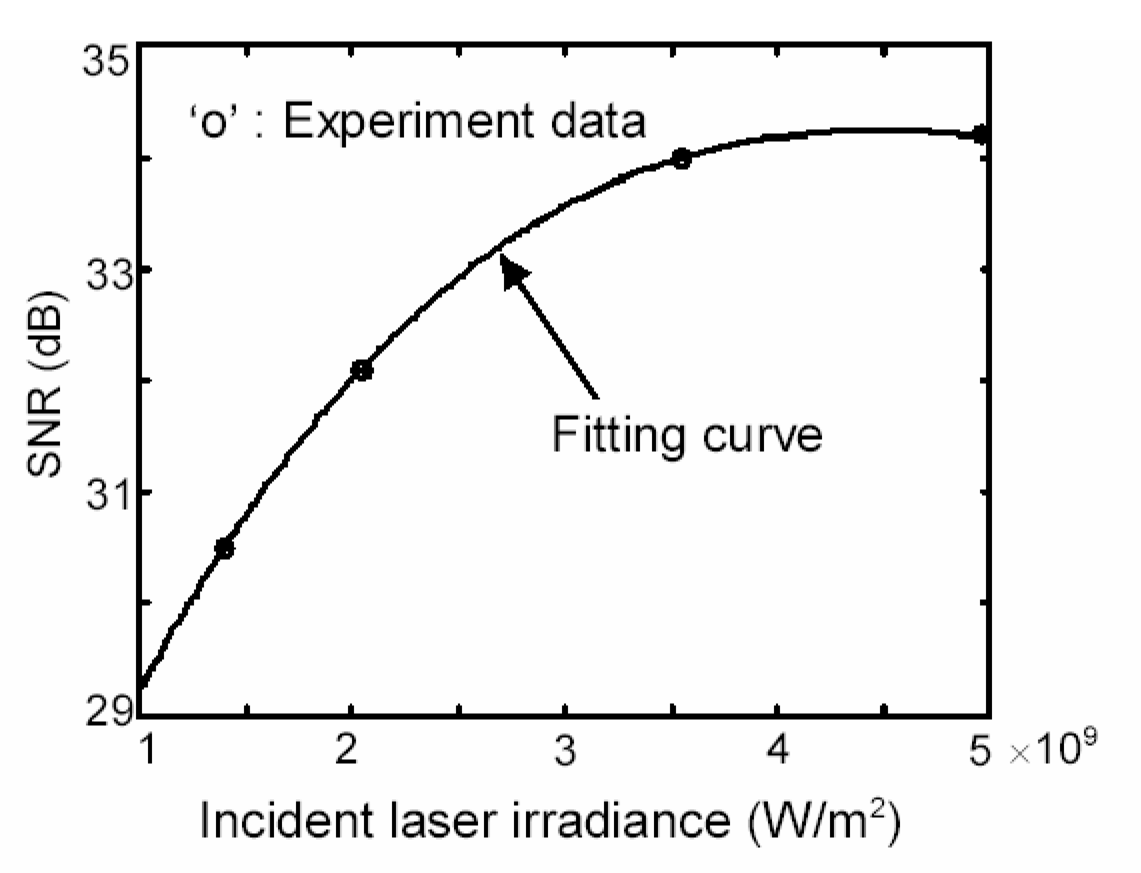
Limited cycle time per molecule (~10ps)



Maximum number of photons per molecule per sec → max SNR/molecule

Concentration + decay time → Saturation Irradiance

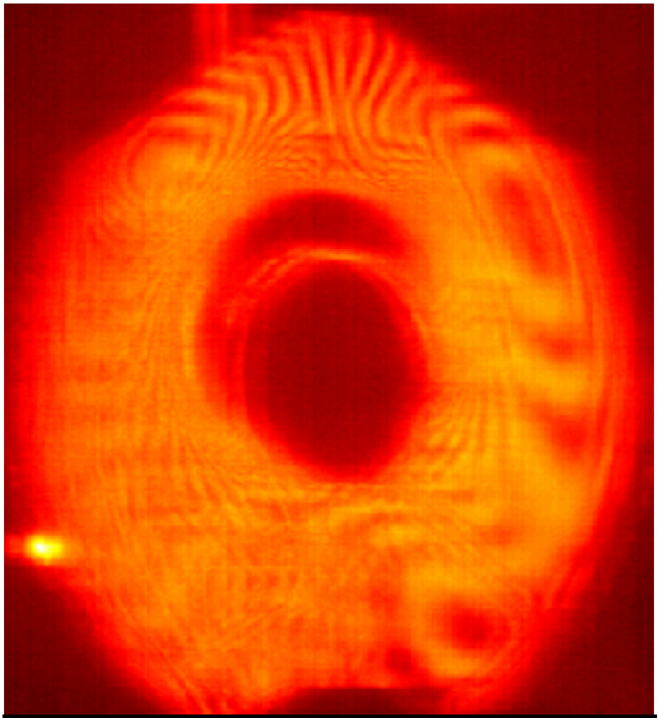
Saturation Irradiance on Readout



Two-Component Media

- Combination of oxazine and fulgimide moelcules creates erasable two-photon fluorescent media.
- Write with 532 nm short pulse
- Read with 650 nm laser diode
- Erase with 400 nm laser diode
- Work done at UC Irvine (Rentzipis *et al.*)

Results of Low-Orbit Environmental Testing with Plastic Media

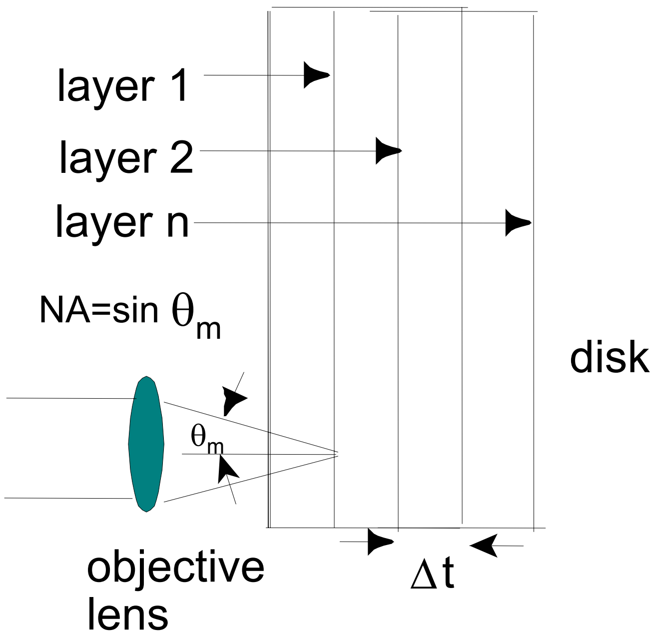


2-Photon disk surface deformation with temperature.

- Plastic substrate deformation with high (> 50 C) temperature leads to servo instabilities → new servo development necessary.
- Insensitive to high-energy ions.
- Sensitive to high-energy protons at exposures greater than 20,000 krad.

Aberration induced in a multi-layer read out system

Far-field system

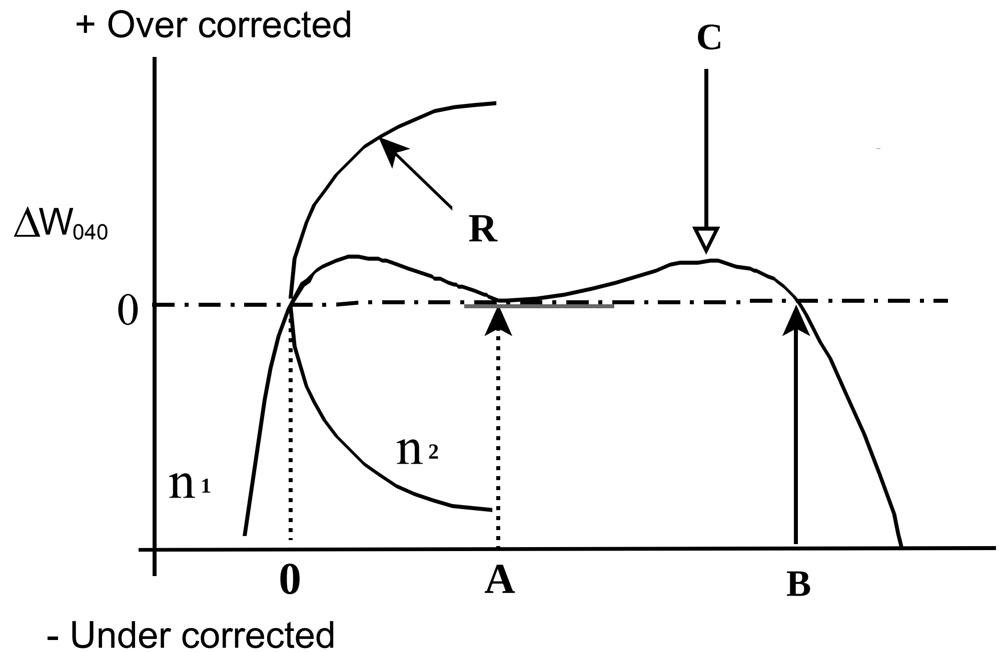


$$W040 = -1/8\, NA^4 \Delta t\, (n^2-1)/n^3$$

NA: Numerical aperture

n: refractive index of the disk

Near-field system



$$W040 = -1/8\, u^4 \Delta L^2\, (n_2^{\ 2}-n_2)/R$$

u: marginal ray angle

ΔL: shift of focus from point A

R: radius of SIL

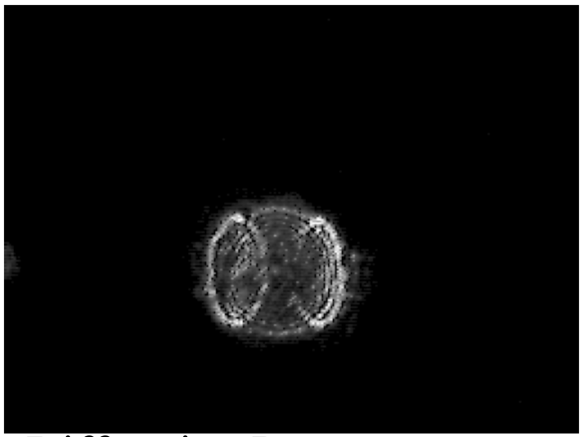
A: SIL hemisphere

B: SIL aplanatic hyper-hemisphere

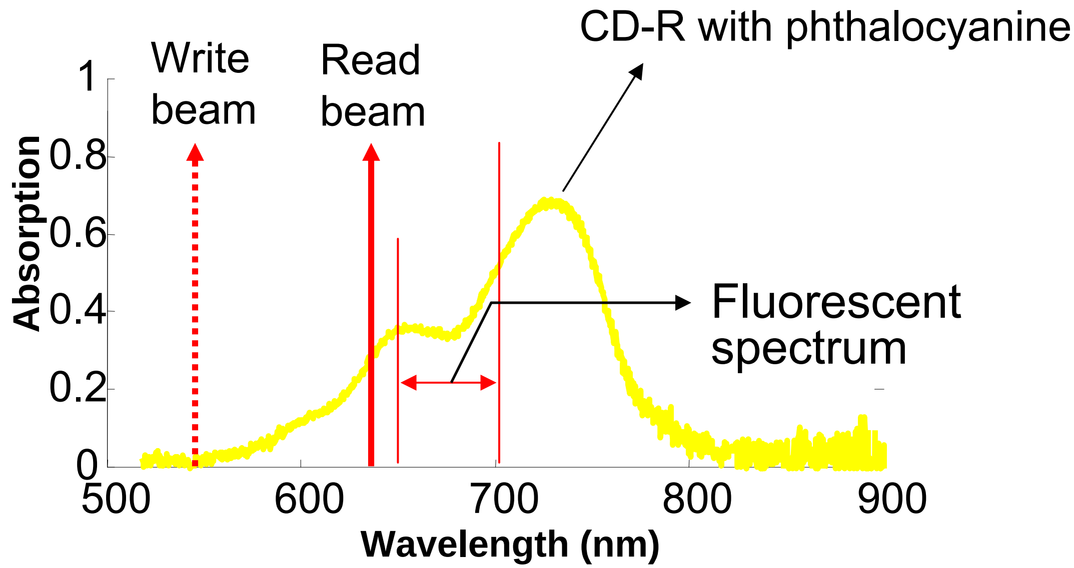
C: Stable point

D: Stable point

AEM : Lock of Focus and Track with Reference Disk Structure



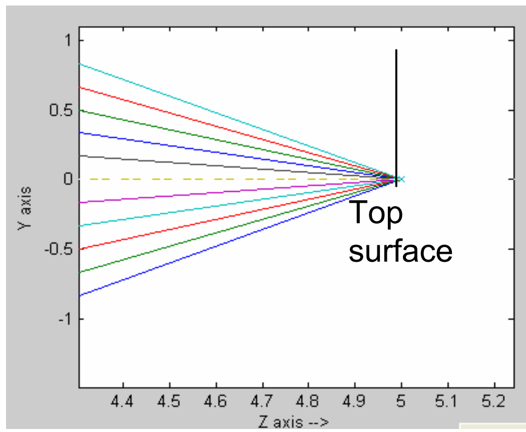
Diffraction Pattern
of Slave Beam
from CD-R data layer

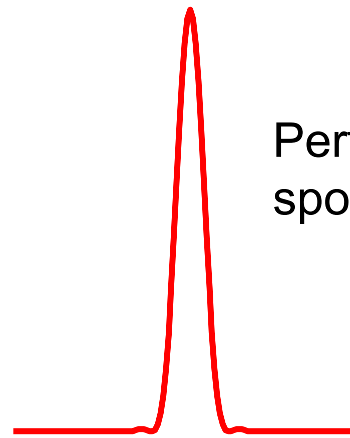


- The absorption spectra of several kinds of commercial CD-Rs are measured to determine the wavelength of writing beam.
- CD-Rs with phthalocyanine show low absorption at 532 nm.
- Stable track lock of slave beam is achieved.

Focusing Through Media

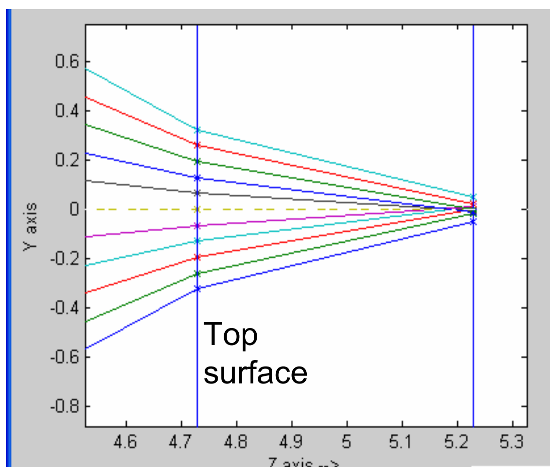
Focus on
surface
(Top Layer)

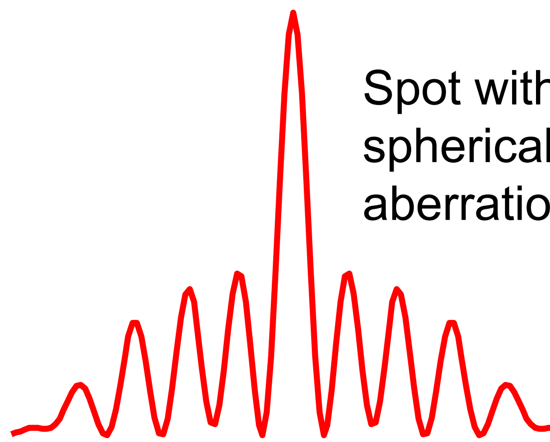




Perfect
spot

Focus deep
inside
medium



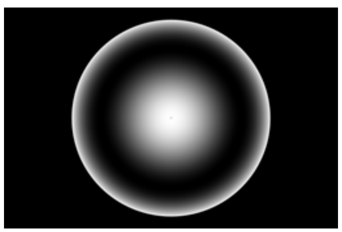


Spot with
spherical
aberration

AEM : Wavefront Compensator

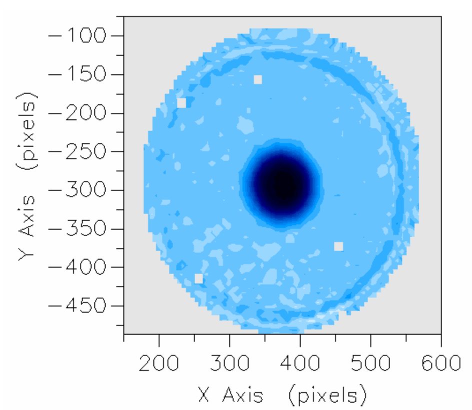
Photoresist Compensator

- The inversed profile of OPD plots is made on photoresist surface to make residual OPD cancelled.



Mask

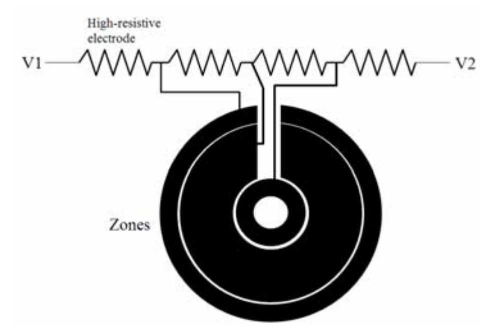
Wavefront profile through the PR plate



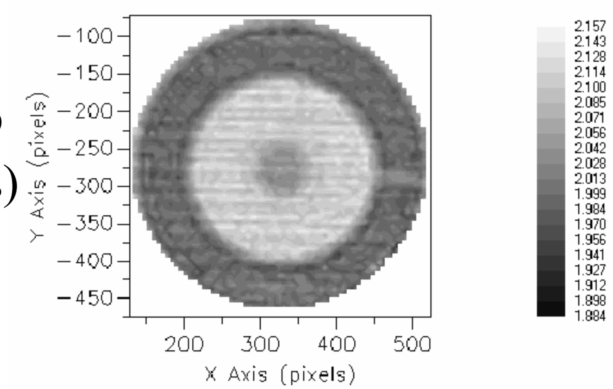
0.5 waves compensated

Liquid Crystal Compensator

- The phase difference along radial lines of Liquid Crystal device is used.



V2= 3 Vp-p (0.27 waves)



0.27 waves compensated

Wavelength-Domain Tracking (WDT)

(Taeyoung Choi)

1) <u>Basic Concept</u>

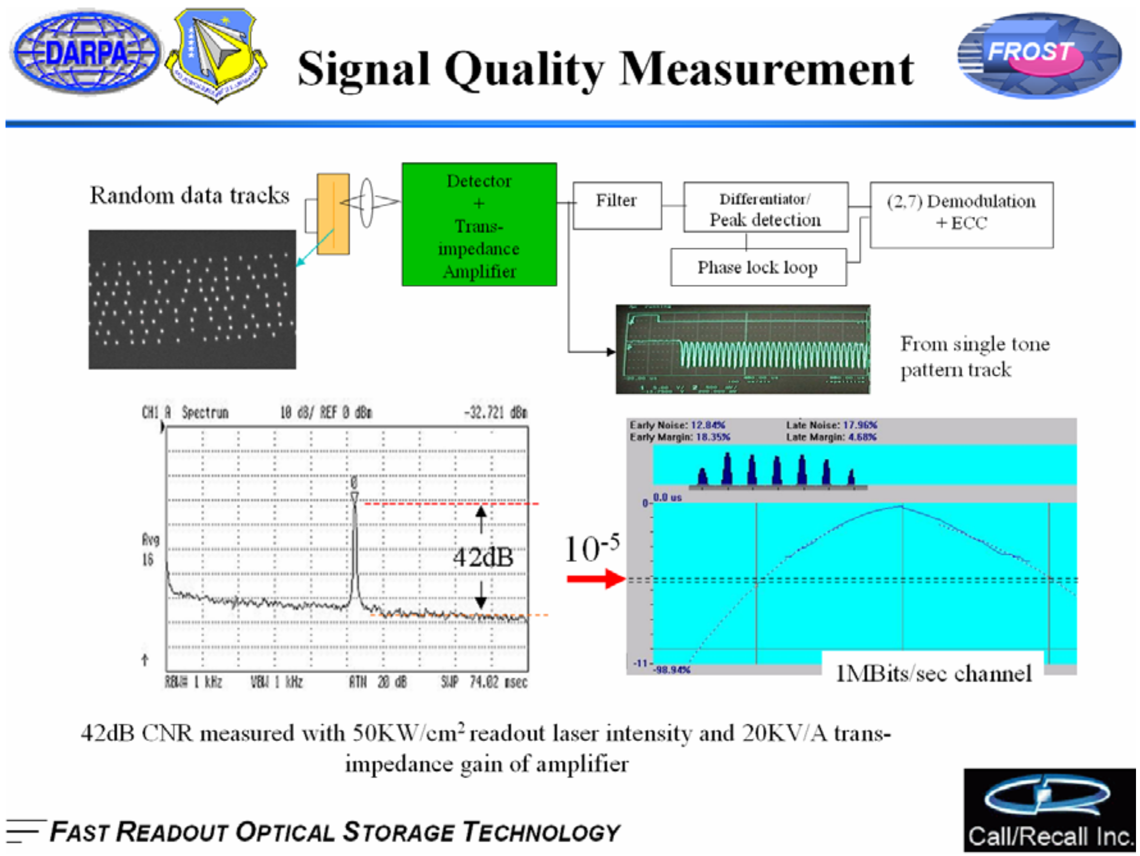
- Wavelength multiplexing
- Individual beam track-following by wavelength tuning
- Error signal extraction by low-frequency modulation

2) <u>Why WDT?</u>

- Present multiple-beam optical storage systems
  - Various methods have been implemented (grating, diode array, separate diodes with beam combiner)
  - Simultaneous recording on multiple tracks
  - Very difficult to control spacing of beams as a function of disk radius
  - No way to individually control spacing
- WDT
  - Simultaneous recording on multiple tracks
  - Individual track-following of multiple beams

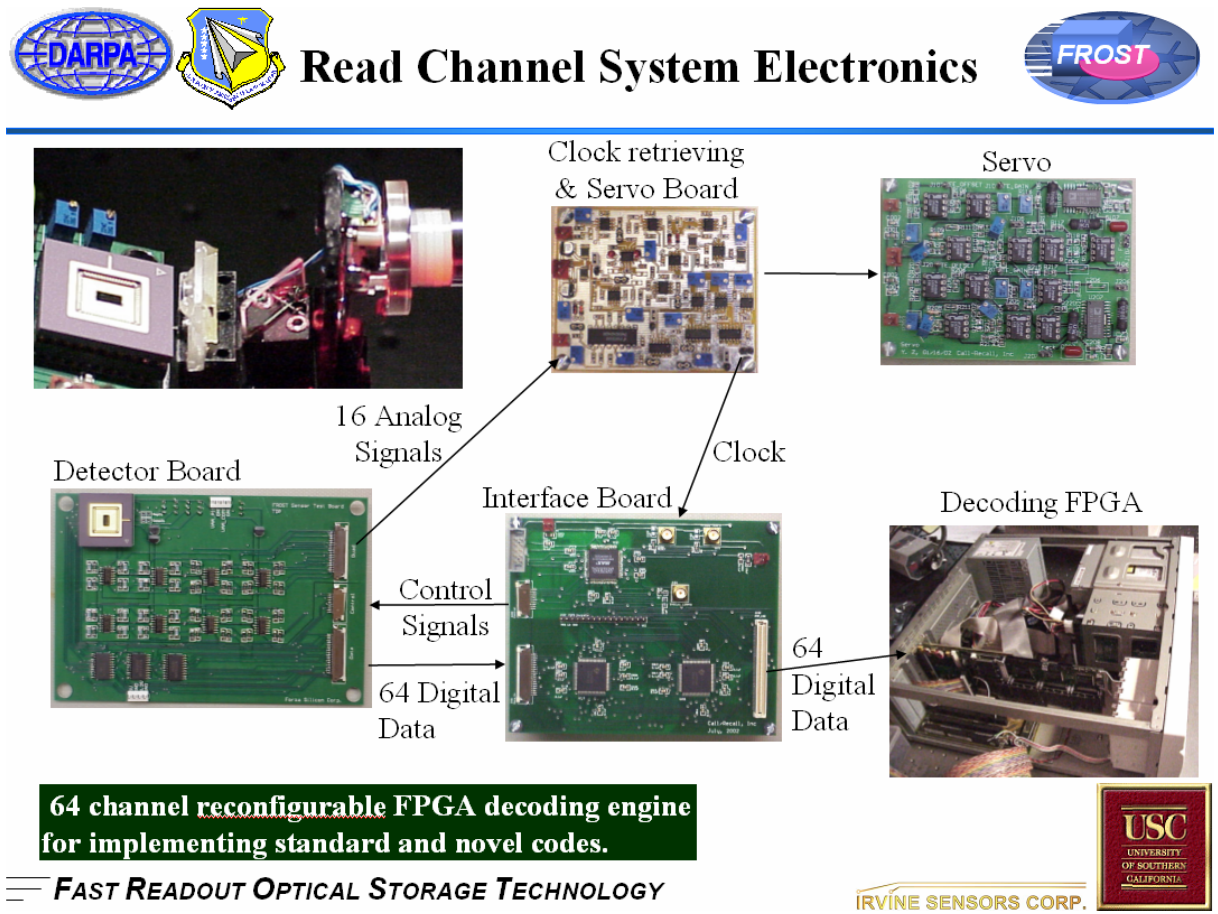
2003 Highlight Graphics

Demonstration at C/R of 10^-5 Raw BER at 1Mb/sec

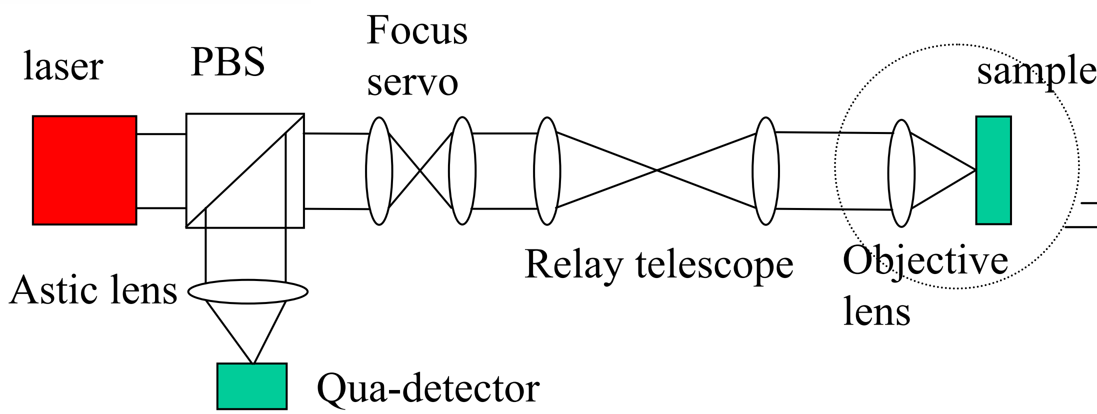


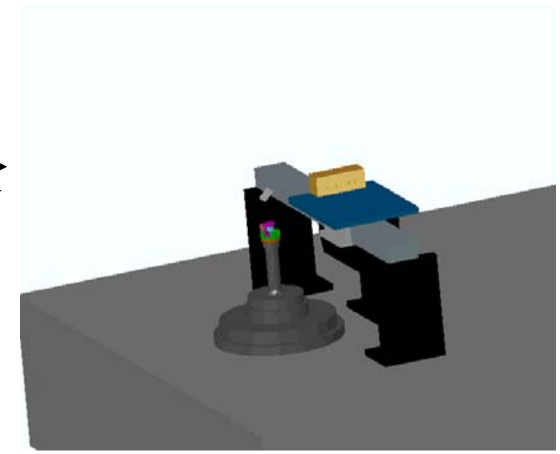
2002 Highlight Graphics (cont.)

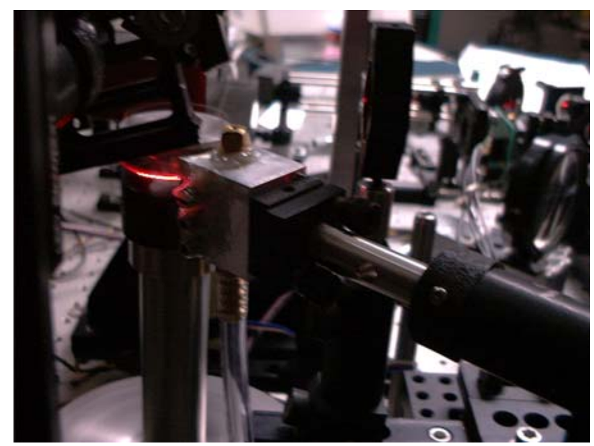
Demonstration of Multiple-Channel Readout at C/R



Dynamic testing: Experiment setup







System specification

(a) The Geltech lens is mounted on a rotating head.

(b) Sample is mounted on a curved surface

(c) Two Geltech lens is used to dynamically compensate the defocus. One of the geltech lens is mounted on an actuator

(d) The compensation range is $\pm 130\mu m$

Student/Staff Support and Publications

- Student Support (Full and Partial)
  - 3 M.S. Degrees
  - 2 Ph.D. Degrees
  - ~3000 hours undergraduate training
- Staff Support (Partial)
  - Electrical engineer, mechanical engineer and research technician (~ 1000 hours)
- Publications
  - Three invited NASA Presentations
  - Five Optical Data Storage conference presentations
  - Six refereed journal publications (in process)

NAND FLASH TECHNOLOGY

Solid State Mass Storage

Pierre Woerlee
Philips Research labs

Summary

- NAND Flash memory will scale to at least 45 nm dimensions (with 2 bits per cell).
- 4GByte on a single IC is possible around 2010-2012.
- Read and write performance approaches HDD (10's MB/s).
- Cost will drop to around 10$ per GByte around 2010.

Message: anything that can be solid state will become solid state (rewrite-able, portable and enough (< 10GB))

How Optical Data Are Stored